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UNIVERSITY OF ALBERTA

WATER DISTRIBUTION CORROSION STUDY, CITY OF YELLOWKNIFE, N. W.T.

BY

RODERICK M. FACEY

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of MASTER of SCIENCE.

IN

ENVIRONMENTAL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

Edmonton, Alberta
SPRING 1992

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled WATER DISTRIBUTION CORROSION STUDY, CITY OF YELLOWKNIFE, N. W. T. submitted by RODERICK M. FACEY in partial fulfilment of the degree of MASTER SCIENCE in ENVIRONMENTAL ENGINEERING.

Daniel W. Smith

Daniel W. Smith

Steve Hrudey

Samuel A. Bradford

Samuel A. Bradford

DATE 11 Oct 91

This Thesis is

In Dedication to

my Parents

For Their Support

Abstract

A corrosion study was undertaken in the City of Yellowknife, N.W.T., to assess the ductile iron corrosion problem within the water distribution system. The purpose of this investigation was to determine the severity of the corrosion problem and to recommend remedial actions. The investigation revealed that the problem is directly related to the water chemistry, the chemical treatment used and to the presence of corrosion-causing bacteria. Test results revealed chemical treatment increases the corrosivity of the supply water. In the case of ductile iron, corrosion increased by 40% from exposure to the treated water. Similarly, for copper the increase was by 65%.

Preliminary sampling showed corrosion-causing and corrosion-intensifying bacteria to be present in low concentrations in the untreated water and absent from the treated water. However, corrosion scales extracted from the distribution system, indicated very high concentrations of corrosion-causing and corrosion-intensifying bacteria. Examples of corrosion-causing microorganisms identified include heterotrophic iron, sulfate, sulfite, and thiosulfate reducing bacteria. Examples of corrosion-intensifying microorganisms identified include sulfur and iron oxidizing bacteria.

In-situ tests results showed Yellowknife's corrosion problem to be moderate. It was determined that the service life of ductile iron is moderately reduced by exposure to the treated water, where as, for copper, the effect is minimal.

To investigate the problem of ductile iron corrosion, a laboratory study was conducted to evaluate possible corrosion inhibitors that could be added to the potable water. Based on the laboratory results, two chemical combinations were identified as most promising: sodium hexametaphosphate and the combination of lime, carbon dioxide and sodium hydroxide. The recommended sodium hexametaphosphate concentration is between 1 mg/L and 2 mg/L as P. The recommended dosages for: lime, carbon dioxide and sodium hydroxide corresponds to Merrill's and Sank's definition of a well-conditioned water with a $CaCO_3$ precipitation potential between the range of 4 mg/L to 10 mg/L as $CaCO_3$.

A solution to Yellowknife's corrosion problem requires several corrective measures. Mechanical cleaning is recommended as a first step to reduce the expected adverse interaction between the corrosion inhibitors and existing scale formation, and to remove bacteria contained in the deposits. Lastly, the application of an inhibitory chemical alone, or as a supplement to a new protective pipe lining would serve to further reduce the corrosion rates.

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1.0 Introduction

1.1 Scope of Work

The study was undertaken to evaluate the corrosivity of Yellowknife's treated supply water and its effect on the water distribution system. As part of this study, the use of corrosion inhibitors was investigated for protecting against corrosion. The study was divided into three phases of work. For phase 1, the study involved performing in-situ corrosion tests at Pumphouses 2 and 4 in Yellowknife, N.W.T.. The objectives were to determine the long term average corrosion rates for ductile iron and copper exposed to the untreated and treated supply water. As well, phase 1 was to assess the severity of the corrosion problem by comparison to other communities. Test results were compared to studies conducted for Greater Vancouver, B.C. and Edmonton, Alberta.

For phase 2, the study involved performing laboratory batch tests in Edmonton, at the Environmental Engineering Laboratory, University of Alberta. The objective was to test various inhibitory chemicals which could be added to the potable water for reducing ductile iron and copper corrosion.

For phase 3, the study involved the microbiological examination of the untreated and treated supply water, and corrosion tubercles for the presence of corrosion-causing and corrosion-intensifying bacteria. The objective was to determine if bacteria could be considered a potential contributor to Yellowknife's corrosion problem.

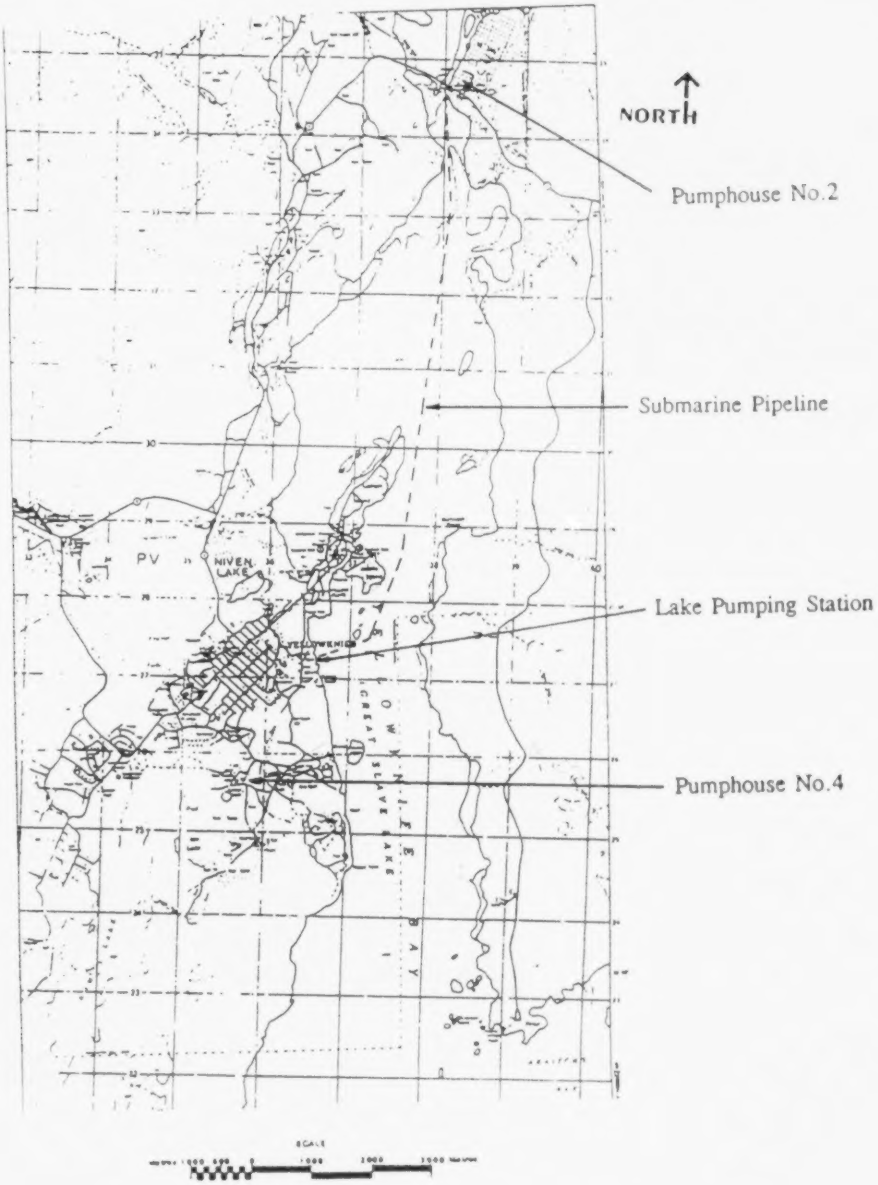
1.2 Background

Yellowknife, N.W.T., is located on the west shore of Yellowknife Bay, on the north arm of Great Slave Lake (see Figure 1.2.1). The topography is flat with many rock outcrops. Surface geology is typical of the Precambrian Shield and consists mainly of granites, volcanics, sediments and lake intrusions. Much of the landscape is covered with muskeg as well as numerous small lakes, while permafrost is discontinuous. Black and white spruce are the predominant vegetation, although pine, birch and popular strands are found in the valleys and occasionally on the sand plains (CWSS, 1981; N.W.T. Data Book, 1986/87).

Yellowknife experiences the extreme climate changes and isolation typical of a northern community. For example, mean high and low temperatures for July have been reported at 20.7 °C and 11.8 °C, respectively, while mean high and low temperatures for January have been reported at -24.7 °C and -33.0 °C, respectively (N.W.T. Data Book, 1986/87). A typical mean annual precipitation is 267 mm, of which 150 mm was rainfall (N.W.T. Data Book, 1986/87).

The community's year round source of domestic water is the Yellowknife River. Water is obtained prior to entering the Bay from an intake located near the Yellowknife River mouth and is then transported to both the City and two mining installations by a submarine supply pipeline. The submarine supply pipeline, situated on the bottom of the Back Bay, consists of a 400 mm diameter steel pipeline with welded joints. This pipeline has an inside epoxy lining and an outside extruded

Figure 1.2.1
City of Yellowknife Map


NORTH
Pumphouse No.2
Submarine Pipeline
Lake Pumping Station
Pumphouse No.4
PV
NIVEN LAKE
YELLOWKNIFE
YELLOWKNIFE BAY
GREAT SLAVE LAKE
SCALE

Adapted from Stanley Associates Engineering Ltd., 1986.
Water Supply And Treatment Study-Final Report.

polyethylene jacket, with the inside epoxy lining burnt off at the weld joints.

A total of four pumphouses are used to distribute water. Pumphouse No. 2, adjacent to the Yellowknife River, draws water from the river to supply the community. The water treatment facilities are housed in the Lake Pumping Station (Pumphouse No. 1). The Lake Pumping Station supplies water directly to the distribution system serving the entire City except for areas in the south. Pumphouse No. 3 distributes water to the Mattonabee area, Forrest Part Stage 2, Northland Trailer Park, and to both the Hospital and the Correctional Centre. Pumphouse No. 4 distributes water to the Frame Lake South Subdivision.

The water distribution system is constructed mostly underground and for the most part is considered conventional in design to systems used in Southern Canada, except that recirculation and heating is provided for protection against freezing. The distribution system is composed mainly of the materials cement-lined ductile iron and type K, copper piping; however, in the older sections of the distribution system unlined cast iron piping is used. Water is distributed to the central business district and surrounding residential area using 150 mm diameter and larger cement-lined ductile iron pipelines. The return lines are single 100 mm diameter ductile iron pipelines. For protection against freezing, pipelines are heat traced and insulated; however, certain sections still rely on bleeding for protection against freezing. Building service line connections are commonly 25 mm diameter, type K, copper piping.

The distribution system has included two underground water storage reservoirs, one of which is located at Pumphouse No. 3 and has a capacity of 2,273 m^3. The other reservoir is located in the Frame Lake South Subdivision and has a capacity of 5,683 m^3. Both reservoirs are designed to provide flow equalization and satisfy fire flow demands.

Yellowknife is not solely serviced by the distribution system. Residents living in Old Town and on Lathan Island receive water via surface pipes in the summer and by truck delivery in the winter (CWSS, 1981; N.W.T. Data Book, 1986/87).

Water treatment consists of fluoridation, chlorination and, during the winter, the addition of heat. The City presently chlorinates to obtain a total residual concentration of 1.0 mg/L and this residual is primarily free chlorine. Hydrofluosilicic acid is used to fluoridate the water to obtain a total concentration of 1.0 mg/L as F. During the winter, the water is heated to about 4 °C (SAEL, 1986; N.W.T. Data Book, 1986/87).

Water from the Yellowknife River is of good chemical quality for domestic use. Shown in Table 1.2.1 are value ranges of certain water quality parameters for throughout the year (Facey & Smith, 1990; SAEL, 1986; CWSS, 1981). In general, the water is very soft, slightly acidic, poorly buffered, and low in dissolved solids.

Protection of the distribution system against internal corrosion is provided by protective coatings present on the pipes when they are newly installed. The ductile iron piping and the raw water submarine pipeline have protective inside and outside coatings. The ductile iron piping has an

Table 1.2.1
Water Quality Data for Yellowknife's Raw and Treated Supply Water Compared to the Canadian Drinking Water Guidelines (GCDWQ, 1989)

Parameter	GCDWQ (1989)	Raw Water (Jan. 29, 91)	Treated Water (Jan. 29, 91)
Antimony	(a)	<0.0005	<0.0036
Arsenic	0.05	0.0003	0.0004
Asbestos *	(b)	<20,000	<20,000
Barium	1.0	0.001	0.013
Boron	5.0	<0.01	<0.01
Cadmium	0.005	<0.003	<0.003
Chloride	250	2.0	4.0
Chromium	0.05	<0.006	<0.006
Copper	1.0	<0.01	0.10
Cyanide	0.20	<0.001	<0.001
Fluoride	1.5 (c)	0.1	0.9
Hardness (as $CaCO_3$)	not defined	14.2	14.1
Iron	not defined	<0.02	<0.02
Lead	0.01	<0.002	<0.002
Manganese	not defined	<0.003	<0.003
Mercury	0.001	<0.0001	<0.0001
Nitrite & Nitrate	10.0	0.05	0.05
pH	6.5 to 8.5	6.8	6.6
Selenium	0.01	<0.0002	<0.0002
Silver	not defined	<0.05	<0.05
Sodium	(d)	2	2
Sulfate	500	<1	<1
Total Dissolved Solids	500	<21	<22
Trihalomethanes **			
Total	0.350		
$CHCl_3$	not defined	NP	0.023
Zinc	5.0	<0.005	<0.005
Aluminum	not defined	<0.06	<0.06
Bicarbonate	not defined	19.7	15.6
Beryllium	not defined	<0.001	<0.001
Calcium	not defined	4.5	4.5
Cobalt	not defined	<0.01	<0.01
Conductivity (umhos/cm)	defined by TDS	45.0	50.0
Magnesium	not defined	1.63	1.61
Molybdenum	not defined	<0.02	<0.02
Nickel	not defined	<0.02	<0.02
Phosphorus	not defined	<0.1	<0.1
Potassium	not defined	<1	<1
Silicon	not defined	3.17	0.73
Thallium	not defined	<0.01	<0.1
Titanium	not defined	<0.003	<0.003
Total Alkalinity (as $CaCO_3$)	not defined	16	13
Total Organic Carbon	not defined	10.1	7.8
Turbidity (NTU)	<1.0, <5.0	4.7	0.6
Vanadium	not defined	<0.003	<0.003

Note; all values are expressed as mg/L unless stated otherwise
NP= not present
* Expressed as fibers/L
** THM's values: only chloroforms measured

(a) An objective concentration only was set in 1978, based on health considerations. For Antimony the objective concentration is less or equal to 0.0002 mg/L.

(b) Assessment of data indicates no need to set numerical guide

(c) It is recommended, however, that the concentration of fluoride be adjusted to 1.0 mg/L which is optimum level for the control of dental caries. Where the annual mean daily temperature is less than 10 °C, a concentration of 1.2 mg/L should be maintained.

(d) It is recommended that sodium be included in routine monitoring programs since levels may be of interest to authories who wish to prescribe sodium-restricted diets for their patients.

inside cement-lining and a tar outside coating. The raw water submarine pipeline has an epoxy inside lining and an extruded polyethylene outside jacket, with the inside lining burnt off at the weld joints. The City was unable, at the time of the study, to provide pipe samples for assessment of the cement lining of the ductile iron piping. It is, however, likely that because the water is highly undersaturated with respect to $CaCO_3$, it is corrosive to the cement lining.

According to the City of Yellowknife, only at particular points in the distribution system is corrosion a severe problem. The corrosion problem within the distribution system that has been indicated worst appears associated with the old, unlined cast iron piping located along School Draw Road. Residents in this area have complained about "guck" from these pipes. As well, the City acknowledges past corrosion problems in Pumphouses No. 1 and 4. Shown in Figures 1.2.2, 1.2.3, 1..2.4, and 1.2.5 are photographs of corroded ductile iron pipe sections removed from pumphouse 4. The partial cleaning of one of these samples shows corrosion damage to be uniform.

Past studies (SAEL, 1986; GCG, 1984) have shown the City experiencing corrosion problems with its ductile iron piping in Pumphouses No. 1 and 4. GCG Engineering (1984) reported the water as extremely corrosive, with a Ryznar Index value of 12.2. Also reported was the presence of high concentrations of corrosion-causing bacteria and that this combined with water's chemical corrosivity, was responsible for the ductile iron corrosion problems. Inspection of ductile iron pipe sections removed from Pumphouses 1 and 4 noted severe tuberculation. Corrosion tubercles reduce the pipe's hydraulic capacity as well as intensify corrosion

Figure 1.2.2
Corroded Ductile Iron Pipe Section Removed
From Pumphouse No. 4, Yellowknife, N.W.T.

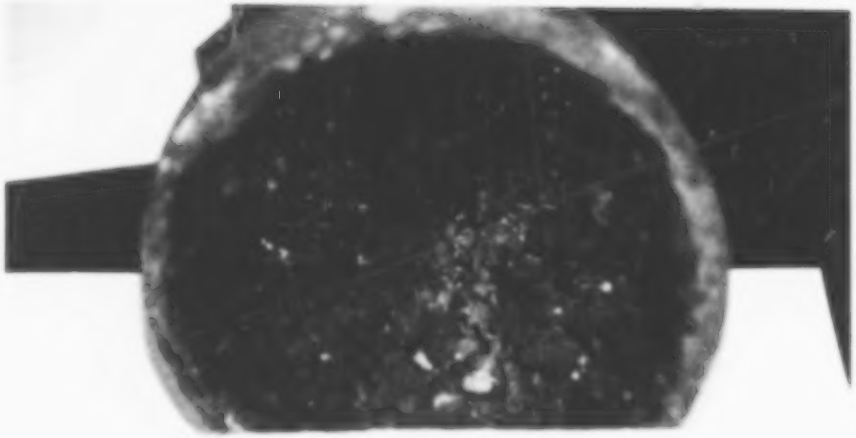


Figure 1.2.3
Corroded Ductile Iron Pipe Section Removed
From Pumphouse No. 4, Yellowknife, N.W.T.

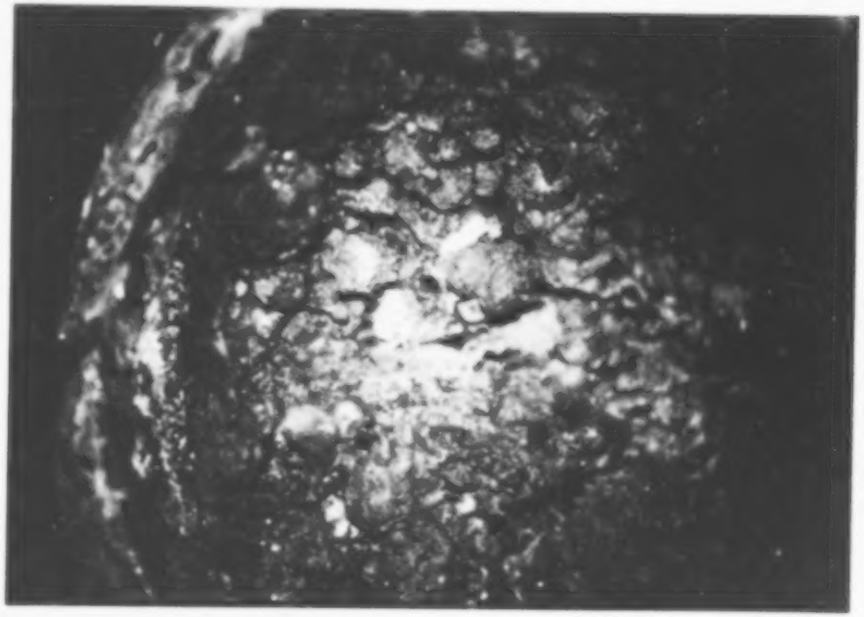


Figure 1.2.4
Corroded Ductile Iron Pipe Section Removed
From Pumphouse No. 4, Yellowknife, N.W.T.

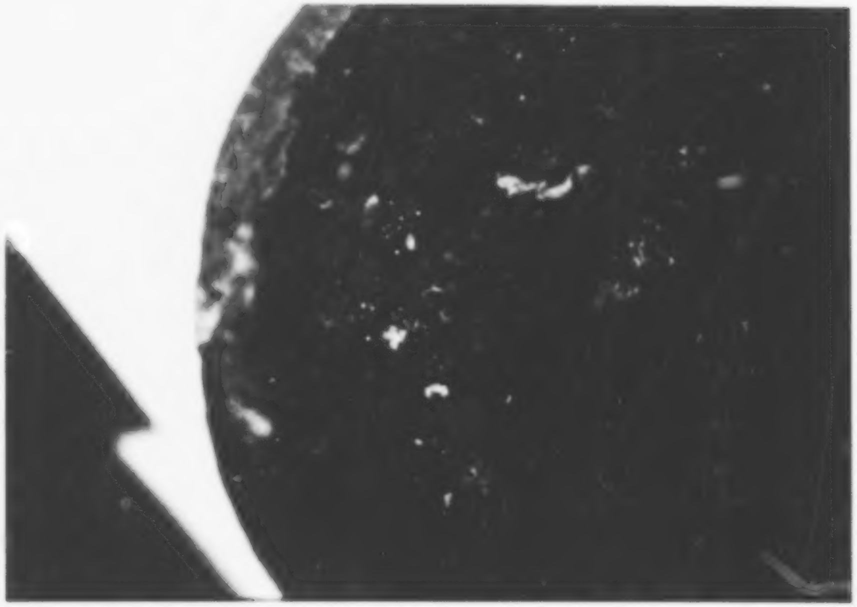
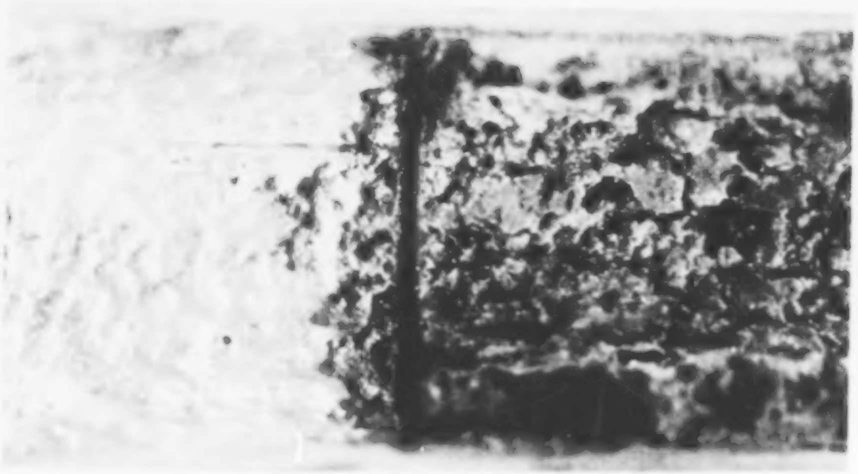


Figure 1.2.5
Corroded Ductile Iron Pipe Section Removed
From Pumphouse No. 4, Yellowknife, N.W.T.



by the formation of concentration cells and by acting as microhabitats for the proliferation of bacteria species capable of causing or intensifying corrosion.

Additional evidence of the chemical corrosivity of the supply water was also reported by Stanley Associates Engineering Ltd. (1986). Similarly, the water was reported as highly undersaturated with respect to $CaCO_3$, and definitely corrosive to $CaCO_3$. As well, water samples collected from the river intake and the Lake Pumping Station showed a marked increase in total iron concentration of 69%. This increase in iron concentration may be attributable to corrosion at the welds of the partly lined steel submarine supply pipeline.

Further confirmation of the corrosion problem was identified by the University with a section of ductile iron pipe removed from the Lake Pumping Station (Pumphouse No. 1). Inspection of this sample noted the presence of excess internal deposits of corrosion tubercles similar to GCG Engineering Ltd. findings (1984). The corrosion tubercles, in some locations, was as thick as 30 mm.

This study was undertaken in response to Yellowknife's corrosion problems, with the underlying motivation to determine the severity of the problem and to recommend a corrosion inhibitor.

2.0 Literature Review

2.1 Introduction to Corrosion

Corrosion is the destructive attack of a material by reaction with its environment to cause a consequent deterioration in its physical properties

(Uhlig, 1985). The material in question is either a metal or a cement based product. Reaction with the environment is either a chemical or an electrochemical reaction and the environment refers to an aqueous media. The material loss by the process of corrosion may be lost by dissolution and/or precipitated as a fused salt onto the material's surface (Uhlig, 1985).

Waters which are corrosive to distribution pipelines and home plumbing systems cause several problems. These problems are grouped into three categories: health, aesthetics, and economics (Kirmeyer & Logsdon, 1983).

Corrosion of materials in both plumbing and distribution systems leading to increased concentrations of metal compounds in the drinking water has prompted serious health concerns. Lead, cadmium, copper, and other metals are present in various amounts in pipe material. The leaching of these substances into the water from the process of corrosion may exceed the maximum concentration limits set by GCDWQ (1989) making the water unsutable for potable use.

Secondary contaminates which are not considered as great a health risk, such as iron and zinc, are also leached to cause problems with aesthetics. These contaminates, when present in concentrations above the recommended limits, can render the water undesirable for consumption because of taste, odour, and/or staining characteristics (Kirmeyer & Logsdon, 1983).

Internal corrosion costs utilities millions of dollars each year as a result of having to replace or repair prematurely deteriorated pipes. The costs associated with the deterioration of plumbing and distribution piping varies depending on the type of material. For example, copper corrosion is usually characterized by the uniform thinning of the pipe wall. Failure is when the structural integrity of the pipe is damaged and replacement is required. In the case of galvanized steel, corrosion is characterized by pits that develop on the surface of the pipe. These pits may eventually penetrate the pipe wall to cause leakage. However, as the pipe deteriorates, tubercles are formed and increase to reduce the pipe's hydraulic capacity. The reduction or loss in the hydraulic capacity of the system leads to higher pumping costs and the eventual cleaning of the system. Consequently, the costs associated with corrosion are extensive and costly.

2.2 Forms of Corrosion

2.2.1 Uniform Corrosion

Uniform corrosion is not customarily encountered in water piping systems unless the material is copper. Copper in close to neutral pH water, will corrode uniformly (Millette, 1985). Microscopic examination shows the metal surface as having small pits that differ in size, depth, diameter, and density, and that this damage is relatively uniform over the metal's surface. This form of corrosion can be easily measured and the service life of the material accurately predicted. Uniform corrosion is not considered a major engineering or maintenance problem in the water industry (Hettiaratchi and Smith, 1990), however, even though the corrosion rate is low, uniform corrosion over a considerable area may impart more impurities into the water than if localized. The addition of significant amounts of corrosion by-products to the drinking water poses a major water quality and health concern.

Uniform corrosion of a single metal occurs when the cathode and anode sites on the metal's surface are interchangeable. That is, a particular site on the metal's surface may be anodic one instant and cathodic the next. The shifting of cathodic and anodic areas about the material's surface causes the rate of material loss to be relatively uniform (AWWA, 1985).

2.2.2 Localized Corrosion

Localized corrosion is subdivided to include the following types of corrosion observed for water distribution systems. The most important are pitting, galvanic, crevice, erosion, and selective leaching.

Non-uniform, or localized corrosion refers to the uneven attack of the metal surface so that some areas are severely affected while the remainder of the surface is not. This type of corrosion occurs relatively fast. Non-uniform corrosion, because it is both rapid and may affect the structural integrity of the pipe, is usually considered an engineering or maintenance problem for the utility (Hettiaratchi and Smith, 1990). Several factors that promote localized corrosion are:

a. areas of high stress;

b. areas of imperfections in both the metal or its oxide film or scale; and

c. exposure to an environment which offers some, but not complete, protection.

These factors produce areas that are anodic and the high potential difference between these regions and the rest of the metal are such that the anode area remains fixed. The anodic area is small with respect to the cathode area and corrosion occurs rapidly in comparison to uniform corrosion. For example, corrosion of steel or cast iron water pipes can be uniform or localized. Localized corrosion of cast iron is commonly referred to as tuberculation. Tuberculation is a type of pitting whereby an active pit is covered by growing mounds of corrosion products. This type of corrosion can lead to a loss in hydraulic capacity (AWWA. 1985).

Metals which rely on resistant oxide films for corrosion protection are particularly at risk for localized corrosion. Protective films may cease to be stable in the presence of particular ions such as chloride or sulfate or in the absence of oxygen. Mechanical damage to the oxide film may also cause localized corrosion. In addition, chemical changes in the environment within the pit frequently militate against self-healing, so once pitting has begun it is unlikely to stop until penetration has occurred (AWWA, 1985).

2.2.3 Pitting Corrosion

From an engineering point of view, pitting is probably the most destructive form of corrosion. The total metal corroded is usually negligible, however, entire systems must often be replaced because of pitting attack (Hettiaratchi and Smith, 1990).

Pitting refers to the formation of a pit where local anodic conditions, caused by areas of high stress or metal imperfections, exist relative to a large cathode area. Pits can be of various shapes and sizes, and the degree of attack from mild to severe (Kirmeyer & Logsdon, 1983). The formation of pits is believed to occur in two distinct stages. First, there is an incubation period during which the pits are initiated, then there is a propagation period during which the pits develop and penetrate into the metal (Hettiaratchi and Smith, 1990).

Tuberculation is a type of pitting associated with ferrous materials whereby an active pit is covered by growing mounds of corrosion products. For copper, pitting (type 1) is the most common type of localized corrosion of cold water systems in the United States (AWWA, 1985). A second type, which is less common, is hot-water pitting or type 2 pitting. One visual characteristic of type 1 pitting is a pit that is deep and narrow. Typically, this type of pitting is observed in cold-water systems and penetrates the pipe wall in a short period of time. Type 1 pitting is caused, apart from the influence of the water composition, by factors mostly due to the fabrication of the copper piping (AWWA, 1985). According to Cruse (AWWA, 1985) and Franque (AWWA, 1985) the inception of pitting is associated with the condition of the metal before it is exposed to the water, and propagation of the pit is a function of the water quality. Detectable amounts of carbon present in the composition of copper is suspected as a cause of the pitting.

The less common type of pitting is type 2 pitting. This has been reported to occur for soft, upland waters containing manganese and produces a pit narrower than type 1 (AWWA, 1985). Type 2 pitting rarely occurs for water temperatures of less than 60 °C, restricting this type of corrosion to hot water plumbing systems.

2.2.4 Galvanic Corrosion

Galvanic corrosion occurs when dissimilar metals are coupled together in an aqueous solution and the elements of the corrosion cell are present. The metal which is the less noble of the two, will serve as the anode and thus deteriorate, affording protection to the cathode metal. The rate of galvanic corrosion will depend on the extent of the dissimilarity of the metals coupled, the relative surface areas of the two metals, and the mineralization or conductivity of the solution.

Galvanic corrosion also occurs in single metals. The graphitization which occurs in cast iron is the result of galvanic effects (La Que, 1964). Grey cast iron is characterized as being comprised of carbon in the form of graphite flakes interspread throughout the iron matrix. Both graphite and carbide in cast iron are substantially more noble than iron; therefore accelerating corrosion of iron by galvanic effects. The advantage of ductile iron versus grey cast iron, is the reduced area in having the graphite spheroidal in shape and the absence of carbides in the iron matrix. This physical property makes ductile iron more corrosive resistant.

Corrosion of copper piping from galvanic action does not normally occur in water systems. Of the different materials in which the distribution system is comprised of, copper is normally the most noble and therefore functions as the cathode and does not corrode. However, as means of eliminating galvanic corrosion, dielectric couples can be installed.

2.2.5 Concentration Cell Corrosion

Concentration cell corrosion occurs when differences in the total or the type of mineralization of the environment exist. That is, differences in the acidity, metal ion concentration, anion concentration, or dissolved oxygen concentration between two areas on the metal's surface can increase the driving force of the corrosion reaction. The corrosion process will be such to equalize the concentration of the species that affect the corrosion potential.

Common types of concentration cells are those created by different concentrations of dissolved oxygen or hydrogen ion at different sites on the metal surface. The areas for differential oxygenation corrosion are sites which resist the diffusion of oxygen, such as crevices. Crevice corrosion can be classed as a form of concentration cell corrosion, because oxygen concentration differences are frequently the cause (AWWA, 1985).

2.2.6 Erosion Corrosion

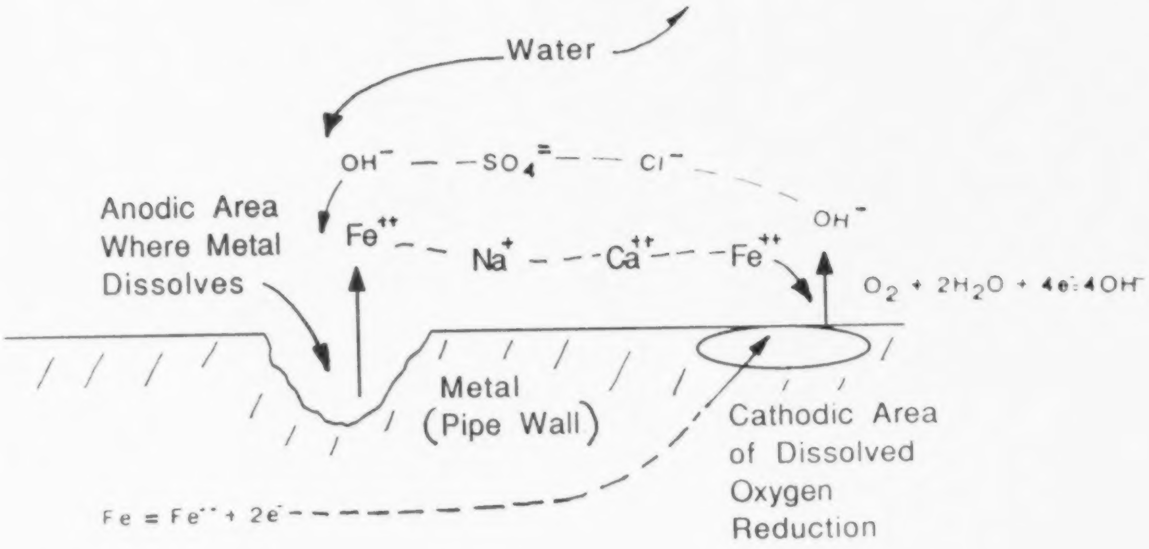
Erosion corrosion is the mechanical wear of the pipe due to turbulence or high flow velocities. Erosion corrosion is frequently found in bends and elbows of piping systems. This type of corrosion is accelerated by localized removal of a protective coating, such as metal oxides and $CaCO_3$.

2.3 Corrosion Kinetics

Internal corrosion of water distribution systems can be chemical, electrochemical or a combination of the two. Generally, for water distribution systems the corrosion process is electrochemical. Electrochemical corrosion can be described in terms of oxidation and reduction reactions (Figure 2.3.1). For corrosion to occur, all the components of an electrochemical cell are required. That is, there must be four factors present. These are:

a. an anode whereby the metal is oxidized resulting in electrons being released;

Figure 2.3.1
Electrochemical Corrosion


Water
Anodic Area
Where Metal
Dissolves
OH⁻ — —SO₄⁼— — Cl⁻
OH⁻
Fe⁺⁺ — Na⁺ — — Ca⁺⁺ — — Fe⁺⁺
O₂ + 2H₂O + 4e = 4OH⁻
Metal
(Pipe Wall)
Cathodic Area
of Dissolved
Oxygen
Reduction
Fe = Fe⁺⁺ + 2e⁻

b. a cathode whereby the electrons released are accepted;

c. an electrolyte, the aqueous media, where there is the transfer of electrolytic current in the form of ions; and

d. a connection between the electrodes to allow for the transfer of electric current in the form of electrons.

Oxidation of the metal occurs at the anode. The metal is oxidized from the metallic state to the ionic state, whereby the valence is increased by the release of electrons. The total current produced by this oxidation must equal the total current of all possible cathodic reactions. That is, in addition to the reduction of oxygen at the cathode, the reduction of other electron deficient species can occur. For example, the reduction of protons and other electron deficient species can include the reduction of H_2O, Cl_2, HOCl, ClO_2, and SO_2. Metal wastage occurs at the anode and the amount lost is chemically equivalent to the reactions at the cathode (AWWA, 1985).

At the cathode, electrons released by the anodic reaction are accepted by either hydrogen, oxygen, and by other electron deficient species depending on the potential. The electron acceptor, however, is usually oxygen for the pH range of 4 to 10 (Rozenfeld, 1973). Typically, the reduction of hydrogen may be neglected in the case of potable waters since the pH is above 6.5.

In order for both anodic and cathodic reactions to proceed, it is necessary that both electrons and ions be transferred. Also reactants and products of the corrosion process must be transported to and from the bulk solution.

The overall rate of corrosion will be controlled by the slowest step in the electrochemical process. This step, considered rate-limiting, may occur at the anode, cathode, or be limited by the rate of conduction in both the metal or the electrolyte (AWWA, 1989). The step which is rate-limiting will be dependent on the conditions within the distribution system. For the purpose of controlling corrosion, it is important to be able to identify the slowest step of the total process. To inhibit the slowest step will provide for the greatest corrosion reductions.

The literature review will pertain to the research. Discussed are the electrochemical reactions and resultant corrosion scales formed for both ductile iron and copper.

2.3.1 Ductile Iron Corrosion

Practical observations and investigations have shown that the corrosion of iron exposed to drinking water is slowly influenced by the composition of the water (AWWA, 1985). Kuch (AWWA, 1985) demonstrated the initial corrosion of iron in oxygenated water, as being primarily controlled by the diffusion of oxygen to the metal's surface. The oxidation of iron produces the overall reaction (1) whereby iron dissolves to diffuse into a solution where it may undergo numerous secondary and tertiary reactions.

1. $Fe \rightarrow Fe^{2+} + 2e^-$

The basic anodic equation (1) is the resultant overall reaction of a series of adsorption, desorption, and electron transfer described below (AWWA, 1985);

2. $\underline{Fe} + OH^- \rightarrow \underline{FeOH}^-$

3. $\underline{FeOH}^- \rightarrow \underline{FeOH} + e^-$

4. $\underline{FeOH} \rightarrow \underline{FeOH}^+ + e^-$

5. $\underline{FeOH}+ \rightarrow FeOH^+$

6. $FeOH^+ \rightarrow Fe^{2+} + OH^-$ (AWWA, 1985, 1989)

The underlined species, are those which are adsorbed onto the metal's surface. Competitive adsorption of constituents from the electrolyte can impede corrosion by repressing reaction 2 or accelerating to promote reaction 5. Reactions 3 and 4 are the electrochemical oxidation steps that may be influenced by environmental factors, which serve to affect various oxidation states to affect the loss or gain of electrons. Reaction 4 is considered the rate-limiting step of the process (AWWA, 1989).

Oxidized iron, once in solution, may undergo numerous secondary reactions to be precipitated as a scale on the metal's surface. Possible secondary reactions are:

7. $Fe^{2+} + CO_3^{2-} \rightarrow FeCO_{3(s)}$ (siderite)

8. $Fe^{2+} + 2OH^- \rightarrow Fe(OH)_{2(s)}$

9. $2Fe^{2+} + 1/2O_2 + 4OH^- \rightarrow 2FeOOH_{(s)}$ (geothite) + H_2O

In addition, oxygen may further oxidize iron (Fe^{2+}) to the form Fe^{3+} (reaction 10), which in turn may be precipitated as ferric hydroxide (reaction 11).

10. $4Fe^{2+} + 4H^{+} + O_{2(aq)} \rightarrow 4Fe^{3+} + 2H_2O$

11. $Fe^{3+} + 3OH^{-} \rightarrow Fe(OH)_{3(s)}$

The possible secondary reactions which may occur are dependent on the water's chemical and bacterial composition. For example, water low in carbonate concentration favours reactions 8, 9, and 11, yet a high carbonate concentration favours reaction 7. Depending on the type of corrosion, products deposited on the metal's surface may or may not inhibit corrosion. For example, iron hydroxides such as $Fe(OH)_2$ and $Fe(OH)_3$ produce a soft and porous coating which may not inhibit corrosion (Kirmeyer, 1983). Whereas, siderite ($FeCO_3$) produces a dense scale to reduce corrosion (AWWA, 1985).

Tertiary reactions may also occur at the surface. Examples include;

12. $2FeCO_{3(s)} + 1/2O_2 + H_2O \rightarrow 2FeOOH_{(s)}$
(geothite, pseudomorph)

13. $3FeCO_3 + 1/2O_2 \rightarrow Fe_3O_4$ (magnetite) $+ 3CO_2$

The above tertiary reactions consume oxygen, which in turn can lower the rate of oxygen diffusing to the cathode. In addition, other precipitates may be deposited as a result of pH changes that accompany corrosion, or from those formed by the addition of inhibitors such as lime, polyphosphate, or silicate.

Scale formation is a complex process and reactions at the surface vary depending on local conditions at the pipe wall. Its structure will consist of a mixture of corrosion products (i.e. $FeCO_{3(s)}$, $Fe_3O_{4(s)}$, $FeOOH_{(s)}$, $CaCO_{3(s)}$, etc.) (AWWA, 1985).

2.3.2 Copper Corrosion

Corrosion of copper in potable waters is unlike that of iron. Copper does not rust rather it tarnishes. Cruse (AWWA, 1985) suggested the initial anode reaction of copper is as follows:

14. $Cu \rightarrow Cu^+ + e^-$

Cuprous ions are unstable and are rapidly oxidized to cupric ions.

15. $Cu^+ \rightarrow Cu^{2+} + e^-$

The reactions responsible for the formation of different forms of copper corrosion products are not completely understood at this time, but different pathways have been postulated. Reactions to describe the overall anode reactions of copper were suggested by Camp and Messrve (AWWA, 1985) and are as follows;

16. $1/2O_2 + H_2O + 4Cu^\circ \rightarrow 2Cu_2O + 2H^+ + 2e^-$

17. $2OH^- + 2Cu^\circ \rightarrow Cu_2O + H_2O + 2e^-$

18. $Cu^{2+} + 1/2O_2 + H_2O + 2e^- \rightarrow Cu(OH)_2$

For pH's greater than 6, reaction 17 occurs. Reaction 18 depicts the formation of cupric hydroxide which is deposited on the metal's surface to later form cuprous oxide.

Copper will form malachite films and the resultant tubercles will be composed of insoluble copper and calcium salts. Lucey (AWWA, 1985) depicted this reaction as follows:

19. $2CuCl + Ca(HCO_3)_2 + O_2 \rightarrow CuCO_3 + Ca(OH)_2 + CaCO_3 + CuCl_2$

2.3.3 Cathodic Reactions

In addition to the anodic reactions there are a series of cathodic reactions occurring simultantaneously. The predominant cathodic reaction for potable water is the reduction of oxygen and it is described by the following reaction:

20. $e^- + 1/4O_2 + 1/2H_2O \rightarrow OH^-$

This reaction occurs at the surface of the metal to produce hydroxide ions which locally increases the pH. The hydroxide ions produced serve to precipitate iron as $Fe(OH)_{2(s)}$ and $Fe(OH)_{3(s)}$, as well as to change the alkalinity species to increase the carbonate ion concentration. The local increase in pH at the pipe's surface caused by corrosion may also precipitate $CaCO_3$ for waters slightly undersaturated with respect to $CaCO_3$.

There are many other possible reactions that may occur as well, but a cathodic reaction of significance for potable waters is the reduction of chlorine. Chlorine can accelerate the rate of corrosion by the direct increase of the redox potential of the electrolyte to favour metal dissolution, or by undergoing a series of chemical reactions to produce H^+, Cl^-, HOCl, and

OCl^- further increasing the water's corrosivity. The reduction of chlorine is depicted by the following reactions:

21. $Cl_2 + H_2O \rightarrow H^+ + Cl^- + HOCl$

22. $HOCl \rightarrow H^+ + OCl^-$

Chlorine's effect, like oxygen, diminishes with the passivation of the metal's surface with corrosion products.

Two cathodic reduction reactions that may be neglected are the reduction of hydrogen and carbon dioxide:

23. $2H^+ + 2e^- \rightarrow H_2$

24. $2CO_2 + 2H_2O + 2e^- \rightarrow H_2 + 2HCO_3^-$

The reduction of hydrogen becomes significant only below the pH of 4. With the minimum pH of potable waters being 6.5, hydrogen reduction can be neglected. For potable waters, the carbon dioxide concentration is often too low to not greatly influence corrosion (AWWA, 1985).

2.4 Thermodynamics

The principles of thermodynamics are useful for determining if the corrosion of a metal will proceed spontaneously, for a given exposure condition. To determine if the oxidation of a metal will occur spontaneously requires calculating the change in the free energy (ΔG) of the system. If the difference in the free energy levels is negative then the reaction occurs spontaneously and the metal is oxidized to a state lower in free energy than the metal itself. The difference between the free energies is the driving force of the reaction. However, spontaneous oxidation does not necessarily mean the metal will corrode. If the reactions proceed at a negligible rate, the metal can be considered essentially inert. The velocity of the electrochemical reactions is influenced by the potential, which in turn is a function of the type of metal and the reaction products.

To determine the range in which various chemical species are stable, Pourbaix diagrams can be used. Pourbaix diagrams are constructed from calculations based on the Nernst equation and solubility data for various metal compounds. These diagrams are useful for predicting the spontaneous direction of reactions, environmental changes which may prevent or reduce corrosion, and for estimating the composition of corrosion products. These diagrams do not, however, provide information as to the rate at which corrosion reactions will proceed.

For example, the general Pourbaix diagram for the iron-water system shows that when in the form Fe^{2+} or Fe^{3+}, iron corrodes at a high rate. Depending on the potential and pH, solid products such as $Fe(OH)_{3(s)}$, $Fe_2O_{3(s)}$, or Fe_3O_4 may form and deposit on the iron surface to reduce corrosion by passivation. At low pH and low potential, iron can be made immune to corrosion by coupling iron with a metal which is more easily corroded, such as zinc.

The general Pourbaix diagram for copper, unlike that of iron, shows the immunity area for copper extends well into the stability area for water. Copper is shown as either passivated or immune throughout the region for H_2-H_2O-O_2 stability.

2.5 Soft, Low Alkalinity Water Corrosion

Soft, low alkalinity waters are often corrosive when used in contact with metallic materials. Corrosion by soft, low alkalinity waters, however, becomes significant through the use of acid treatment chemicals in water treatment or by the acidification of surface waters by acid precipitation (AWWA, 1985). Low pH, low alkalinity, and low ion concentration influence corrosion. For example, low alkalinity implies low buffer intensity, which has at least two undesirable effects. Firstly, small additions of hydrogen ions through the adding of chemicals will cause significant changes to pH. Secondly, reactions occurring along the pipe's interface to either generate or consume protons can change the driving force for diffusional mass transport to enhance the electrochemical process for corrosion (AWWA, 1985). Low ion concentrations prevent the possibility of forming a protective film of calcium carbonate. This is because pH and the carbonate concentration are low, so that protective coatings of insoluble corrosion products are usually not formed (AWWA, 1985). Instead, scales that are less protective are formed. Low pH solution enhances the electrochemical process for corrosion by increasing the hydroxide ion gradient near the cathode, which in turn increases the diffusive transport of these reaction products. As well, low pH may prevent the formation of protective scales. Waters low in alkalinity have low conductivity which tends to create localized corrosion cells and increase pitting penetration (AWWA, 1985).

Protective coatings may also be greatly affected by exposure to soft, low alkalinity water. For example, the dissolution of cement mortar linings used in ferrous piping may be the result of at least two mechanisms (EPA, 1984). Firstly, is low pH. Low pH water can cause the dissolution of free lime and other compounds. Secondly, the lining may deteriorate due to chemical attack by aggressive ions such as chlorides and sulfates (Montgomery, 1985). However, for domestic waters the dissolution of cement linings is primarily governed by the material's solubility.

2.6.1 Physical Factors Which Influence Corrosion

2.6.1.1 Pipe Material

Material selection is the first stage in the control of corrosion. Selection of a material must be give careful consideration to the source of water to which the material is to be exposed to and to its susceptibility to corrosion. Currently, there are many different types of materials that may be employed which offer good resistance to corrosion. However, the use of such materials is limited in terms of workability, associated economics, and desired life expectancy.

There are a number of factors related to the piping material which influence the rate of corrosion. For example, grain density, imperfections, or damage to a metal's protective oxide film can influence the corrosion potential (Hettiaratchi and Smith, 1990). Materials susceptible to corrosion can be made more resistant by the use of protective coatings. A common protective inside lining for cast iron piping is cement mortar. However, cement mortar linings may dissolve when exposed to soft, low alkalinity waters unless the lining is supplemented by the addition of a chemical inhibitor.

The chemical and physical properties of a material can be greatly modified by the inclusion of various alloys or graphites to either improve or reduce the metal's resistance to corrosion. The typical types of iron-based materials used by water utilities are cast iron, ductile iron, and steel. Table 2.6.1.1 lists the differences in the chemical and physical properties of each (AWWA, 1985).

La Que (1964) reported ductile iron as being more resistant to corrosion than ordinary cast iron. Ductile iron is less susceptible to galvanic effects. In ductile iron, the graphite particles are of a spherical shape, produced from adding small amounts of magnesium. In ordinary cast iron the graphite occurs as flakes. The basic tendency of iron to react with its environment is the same whether iron exists as ordinary cast iron, ductile iron, or steel. However, the rates will be quite different as a result of the relative surface area of the graphite inclusions or carbides. The rate of corrosion is influenced by the surface area of the graphite and carbides. The absence of carbides and the reduced area of graphite in the iron matrix of ductile iron greatly reduces the intensity of galvanic corrosion (La Que, 1964).

The second most common material used in distribution and household plumbing systems is copper. Copper is more noble than most other materials commonly used in distribution systems, with the exception of passivated steels (AWWA, 1985).

Table 2.6.1.1
Physical and Chemical Properties of Ductile Iron, Cast Iron and Steel

Sample	Type	Elemental Composition (%)							Iron (%)
		C	Si	Mn	P	S	Ni	Mg	
Ductile	1-in. block	3.70	2.50	0.45	0.03	0.01	0.60	0.05	92.66
	Pipe Fitting	3.60	2.60	0.48	0.07	0.01	0.85	0.06	
Cast	1.2-in. bar, Class 30	3.35	2.25	0.55	0.20	0.12	N/A	N/A	93.18
Steel	1-in. round	0.15	0.17	0.50	0.03	0.03	N/A	N/A	99.12

Source: AWWA, 1985, pg. 35

Campell (AWWA, 1985) cited manufacturing defects for the inception of pitting of copper piping. He observed that pipes which had failed as a result of rapid pitting often contained a wrinkled film of carbon on the interior surface. Carbon, in relation to copper, is more noble and therefore may cause galvanic corrosion. Residues of carbon films from drawing oils which had been carbonized during annealing were attributed to the rapid pitting of copper piping. Cruse and Pomeroy (AWWA, 1985) found that if carbon was present in detectable amounts, in copper tubes, pitting could result.

2.6.1.2 Velocity

Corrosion rates can be increased by excessively high and very low velocities depending on the water's composition. Velocity is an important factor in the electrochemical process of corrosion for it influences the rate at which ions are transported to and from the bulk solution. Copson (AWWA, 1985) showed velocity as having varying effects on corrosion rates depending on pH, oxygen concentration, galvanic couplings, polarization, and electrode potential.

High velocities may cause erosion corrosion. However, high velocities may also reduce corrosion in aiding in the formation of protective coatings by improving transporting of the inhibitor to the metal's surface.

Chilton (1964) showed the growth of a thick oxide film on copper as being dependent on good electronic and ionic conduction. Velocity will

Chilton (1964) showed the growth of a thick oxide film on copper as being dependent on good electronic and ionic conduction. Velocity will influence ionic conduction, which in turn affects the rate and quality of scale formed. However, velocities in excess of 4 fps were found to increase corrosion by excessive erosion and impingement in copper piping (AWWA, 1985). In the case of ferrous materials, excessive erosion of protective scales increases corrosion. Eliassen et al. (1956) studied the effects of velocity on the corrosion of steel and found the rate of corrosion increased with increasing velocity.

Low flow velocities can increase corrosion by promoting the development of concentration cells. Corrosion reactions at the surface of the metal can change the conditions locally, which along with the presence of various ions can accelerate corrosion. For example, low velocity flow will reduce the rate at which oxygen is transported to the surface of the metal. For areas such as crevices, low flow conditions may result in differential oxygenation corrosion.

2.6.1.3 Temperature

Temperature changes affect the chemical, physical, and biological characteristics of the water, all of which may influence corrosion. As a rule of thumb, the rates of chemical reactions double for every 10 °C rise in temperature (AWWA, 1985). Corrosion reactions increase with increasing temperature and as a result, the rate of scale formation may increase.

The performance of inhibitors also varies with temperature. For example, lime and other pH adjustment chemicals will form more scale at higher temperatures (AWWA, 1989). However, polyphosphates revert to orthophosphate at temperatures above 49 °C, with almost complete reversion occurring. above 71 °C. The effect of increasing the temperature may be a loss of inhibitor capability. In addition, waters high in hardness will deposit more scale at higher temperatures to reduce the efficiency of hot water heaters and if excessive, may seriously impair the pipe's hydraulic capacity.

2.6.2 Chemical Factors

2.6.2.1 Dissolved Oxygen

Dissolved oxygen is one of the most important factors influencing the rate of corrosion of all metals of concern (Montgomery, 1985). Oxygen is a direct participant in the corrosion reaction, accepting electrons at the cathode;

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

The hydroxide ions produced locally can increase the pH at the metal's surface to cause varying effects depending on the water's composition. As well, hydroxides may combine with the metal to produce metal hydroxides which precipitate onto the metal's surface. At most levels of dissolved oxygen, the cathodic reaction is transport limited (Montgomery, 1985). Therefore increasing the dissolved oxygen concentration in the bulk solution increases the rate at which oxygen is transported to the surface; thus the rate at which corrosion occurs.

Oxygen also reacts with the hydrogen (H_2) released at the cathode, effectively removing H_2 and allowing the corrosion reaction at the cathode to continue. This process is called "depolarization" (Hettiaratchi and Smith, 1990).

$$2H_2 + O_2 \rightarrow 2H_2O$$

Oxygen is also responsible for the occurence of "red water." Oxidation of soluble ferrous ions to ferric ions in the presence of O_2 results in the formation of insoluble ferric hydroxide as follows:

$$4Fe^{2+} + 3O_2 + 6H_2O + 8e^- \rightarrow 4Fe(OH)_{3(s)}$$

However, the effect oxygen has on the corrosion of metals diminishes with the passivation of the metal's surface with corrosion scales or oxides (AWWA, 1985).

2.6.2.2 Effect of pH

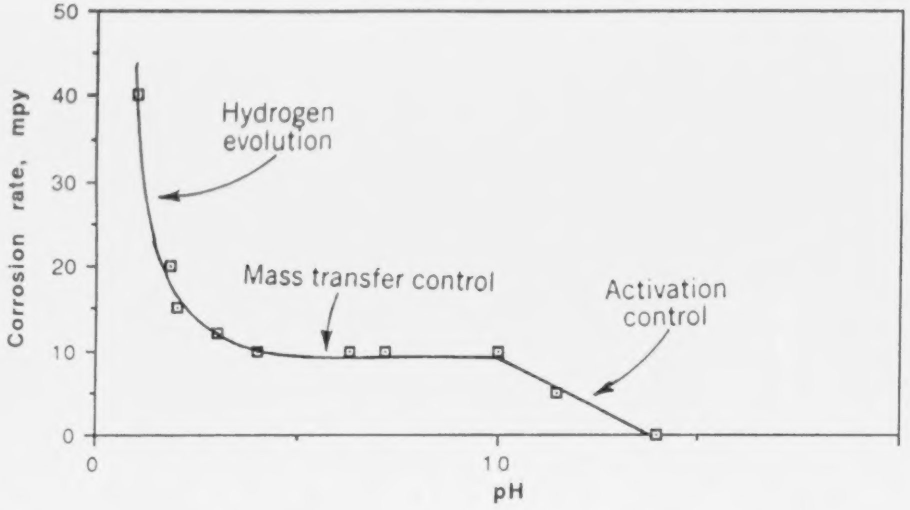
Below the pH of 4 the cathodic reaction is the reduction of hydrogen ion to produce hydrogen gas (Montgomery, 1985). Above the pH of 4, the principal cathodic reaction is the reduction of oxygen in water.

The effect pH has on the corrosion of metal is considered selective and is determined by the behavior of the metal's oxide (Hettiaratchi and Smith, 1990). The parameter pH is the master variable controlling solubility, rates of reactions, and to some extent, the surface chemistry characteristics of metal species in the corrosion reaction (Montgomery, 1985). For example, Larson and Skold (1957) conducted long-term corrosion tests in stagnant, soft waters only, to show corrosion rates increasing with the increasing pH. Stumm (1960) made similar observations concerning the corrosion of cast iron for exposure to varying degrees of saturation. He noted that increasing the pH and the hardness of the water reduced corrosion. The authors (Stumm (1960); Larson and Skold (1958)) illustrated the effect of pH on scale development on the surfaces of iron metals. At lower pH, uniform corrosion was observed. However, at higher pH, increased uneveness and tuberculation was observed (Stumm, 1960; Larson and Skold, 1958). Suggested also, is that pH influences the charge of ferric hydroxide ($Fe(OH)_3$) micelles. At a more alkaline pH, the $Fe(OH)_3$ micelles become negatively charged, causing them to remain at the anode, further increasing the potential difference to increase corrosion (Montgomery, 1985).

The effect of pH on the corrosion of iron is depicted by Figure 2.6.2.1 (Whitman et al., 1924). Shown, is that below the pH of 4 the corrosion rate increased expontentially. Between the pH range of 4 and 10 the corrosion rate is controlled by the rate at which oxygen is transfered to the cathode. Above the pH of 10 corrosion is significantly reduced and is apparently activation controlled (Whitman et al., 1924).

Copper corrosion is very pH dependent in low mineralized waters (AWWA, 1985). The tendency is for copper corrosion to decrease with increasing pH. pH can influence copper corrosion in several ways. Firstly, changing the pH of the solution alters the distribution of species, thus altering the equilibrium potential of all the redox reactions occurring.. Secondly, pH is likely to affect the stability and protective qualities of the passivating scales formed on the metal's surface (AWWA, 1989).

Figure 2.6.2.1
Effect of pH on Iron Corrosion



adapted from Whitman et al., 1924

2.6.2.3 Alkalinity

In drinking water, alkalinity is composed mostly of carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-). Alkalinity is a measure of the water's ability to neutralize acids and this property is called "buffering" (Hettiaratchi and Smith, 1990).

Waters of low buffer intensity produce at least two undesirable effects. Firstly, small additions of hydrogen ion from chemical addition will cause large changes to pH. Secondly, the water is unable to neutralize reactions at the metal interface allowing larger pH differentials to occur, hence increasing the driving force for promoting concentration cell corrosion (AWWA, 1985).

Eliassen et al. (1953) showed buffer intensity to be inversely correlated with the corrosion of iron. Stumm (1960) suggested a desirable minimum buffer intensity of 0.2 meq/L per pH unit.

Alkalinity usually decreases metallic corrosion by forming protective coatings on metal surfaces. For example, alkalinity reduced lead dissolution from lead pipes and lead solder by the formation of a lead carbonate coating (Hettiaratchi and Smith, 1990).

2.6.2.4 Chlorine residual

Chlorine can accelerate the rate of attack of a metal by directly increasing the redox potential of the electrolyte to favour metal dissolution, or by undergoing a series of chemical reactions to produce hydrogen ions, hypochlorous acid, hypochlorite ions, and chloride

(AWWA, 1985). Chlorine can participate directly in cathode depolarization as depicted:

$$Cl_2 + 2e^- \rightarrow 2Cl^-$$

Chlorine, however, is not present as molecular chlorine because it rapidly hydrolyzes to hypochlorite ions given the pH range of potable waters (AWWA, 1985).

Free chlorine has been shown to greatly increase the corrosiveness of water, as compared to chloramines (Ryder and Hoyt, 1977). For example, Larson (1955) noted that the rate of steel corrosion increased when the free chlorine concentration was 0.4 mg/L or more, whereas, chloramines were shown to exert an inhibiting effect on the rate of steel corrosion for the concentrations of 0.4 to 3.6 mg/L as total residual chlorine (Larson, 1957). For copper, chlorine and its derivatives (less than 1.0 mg/L) are considered to not contribute significantly to its corrosion (AWWA, 1985).

Chlorine's effect, however, diminishes with the passivation of the metal's surface with corrosion products.

2.6.2.5 Chlorides

Chloride is the major aggressive ion in the corrosion of metals used to convey water (Montgomery, 1985). It has been particularly noted for the breakdown of passivity in many ferrous alloys and as the main causes of pitting in stainless steels. Hatch and Rice (1959) noted that increasing chloride concentration, increased the rate of steel corrosion. Lorenz (1965) postulated that chloride may act to alter the oxidation reactions of iron and introduce a new rate-limiting step. This stems from chloride's ability to form ligand complexes with iron species. The new rate-limiting step is dependent on the chloride concentration and therefore by increasing the chloride concentration, increases corrosion.

Chemical additions, such as lime or sodium carbonate, to increase alkalinity will reduce the severity of chloride corrosion (AWWA, 1985).

2.6.2.6 Sulfates

Sulfates, like chlorides, also influence the corrosion of ferrous materials (Montgomery, 1985). High sulfate concentrations are a contributing factor to pitting corrosion of copper tubing (AWWA, 1985). However, sulfate ions are deemed less of a factor in promoting crevice corrosion because they are larger and less mobile than chloride ions (AWWA, 1985).

The addition of lime, sodium carbonate, or sodium bicarbonate will tend to reduce the aggressive behavior of sulfate ions. As well, phosphate and silicate inhibitors, having passivated the metal, will also prevent sulfate-related pitting (AWWA, 1985).

2.6.2.7 Hardness

Hardness is the composite measure of the polyvalent cation content of the water. The major polyvalent cations responsible for hardness are calcium and magnesium. Generally, scaling waters tend to be non-corrosive to metals (AWWA, 1985). That is, waters that deposit a tough, adherent, calcium carbonate scale are usually noncorrosive (AWWA, 1985). Treatment of the water to adjust the Langelier Saturation Index (LSI) to a slightly positive value is an approach commonly used by utilities for corrosion control. However, experience has shown, this approach works best when supplemented by field inspections to ensure protection is indeed occurring.. As well, scaling water will not usually protect against impingement attack, for the calcium carbonate deposited is often mechanically eroded as quickly as it is formed (AWWA, 1985).

2.6.2.8 Humic Substances

Some natural organics present in drinking water are known to react with metal. The resulting protective film helps in reducing corrosion (Hettiaratchi and Smith, 1990). Present studies have not shown humic substances to increase the corrosion of metals (AWWA, 1985). Instead, studies have either reported humic substances as having no effect or as having reduced the corrosion of ferrous materials (AWWA 1985, 1989).

2.6.2.9 Nitrates

Wagner et al. (AWWA, 1985) studied the effect of nitrate at different concentrations on the corrosion of iron. Nitrate was shown not to cause any observable effect on the corrosion of iron. However, this is not to say nitrate will not influence corrosion.

Nitrate can substitute for oxygen in the oxidation of ferrous ions by microorganisms leading to the direct formation of hydrous ferric hydroxide. The microbial oxidation of ferrous iron leads to ferric reaction products that are very porous (AWWA, 1985). As a result the scale produced from these porous reaction products is less protective (AWWA, 1985).

2.7 Microbial Induced Corrosion

These exists a vast variety of bacteria capable of causing corrosion. These bacteria are referred to as corrosion-causing and corrosion-intensifying bacteria. Corrosion-causing microorganisms are those bacteria who's activity directly causes corrosion. Corrosion-intensifying microorganisms are those bacteria who's activity contributes to corrosion. Examples of corrosion-causing microorganisms include heterotrophic iron, sulfate, sulfite, and thiosulfate reducing bacteria. Examples of corrosion-intensifying microorganisms include sulfur and iron oxidizing bacteria. Together these bacteria are known to cause or intensify corrosion by several mechanisms. These are (Tiller, 1983):

a. the production of a metabolic by-product corrosive to metals (e.g. H_2S);

b. the creation of biofilms that favour corrosion; and

c. the presence of growths or deposits on the metal surface to encourage the formation of differential aeration or concentration cells causing localized corrosion.

Two forms of microbial activity are associated with aerobic corrosion. This involves the colonization on metal by microbial growths, resulting in deposits or the formation of tubercles. Algae and iron bacteria have been associated with this type of colonization. Algae are only a problem if the distribution system has included open reservoirs. Tubercle formation is the most prevalent and is the result of iron bacteria (Tiller, 1983).

The formation of tubercles has been commonly reported as occurring in iron piping used in water distribution systems (AWWA, 1985). Under these conditions, the mechanism of corrosion is the formation of a differential aeration or concentration cell created by the differences in oxygen concentrations at the tubercle and surrounding environment (Tiller, 1983). Tubercles also serve as microhabitats suitable for the proliferation of other bacterial species capable of causing corrosion. Microscopic examination showed the highest bacterial populations are usually found in encrustations and tubercles (Allen et al., 1980). Within these deposits, the majority of organisms are found on the outer surface of the incrustation, however facultatively aerobic and microaerophilic organisms may survive inside.

The type of environment will influence the different species of bacteria found. The species of bacteria able to intensify corrosion in the aerobic environment are often referred to as slime forming bacteria and include many genera. These bacteria are aerobic oxygen scavengers, capable of harbouring sulfate reducers. This is one method by which they influence corrosion (Tatnall, 1981). The most common are filamentous iron bacteria. Capable of transforming soluble iron to insoluble compounds, iron bacteria are responsible for the formation of hollow, hemispherical tubercles commonly seen on the inside of iron water pipes (Tatnall, 1981). Microscopic investigation of tubercles revealed not only large quantities of amorphous ferric hydroxide, but iron bacteria surrounded by sheaths. The sheath-forming bacteria were lying in coiled balls, strongly incrusted by iron oxides and hydroxides (Olsen and Szybalski, 1949).

Iron oxidizers are considered one of the most nuisance causing bacteria in water. They transform soluble compounds of iron to insoluble compounds such as ferric hydroxide, which may be deposited in a sheath around the organism (Sphaerotillus) or secreted in the form of a stalk or ribbon attached to the cell (Gallionella). The deposition and accumulation of this insoluble material in the distribution system can eventually reduce the pipe's hydraulic capacity. Iron bacteria are also responsible for producing slime, discolouring water, and causing undesirable taste and odours problems (Pelczar et al., 1977).

Iron bacteria are also capable of intensifying corrosion by acting as a catalyst in the redox reactions of iron. These microorganisms derive their metabolic energy from this redox process. The precipitation of iron as an insoluble compound on the metal's surface will further intensify the dissolution of iron.

The most common species found is Gallionella. These bacteria prefer an aerobic or microaerophilic environment. In addition to being able to influence corrosion by the above means, this species can concentrate chlorides in their metabolic deposits to produce a solution similar to a dilute HCl solution. Depending on the metal type, the result may be severe localized corrosion. As well high concentrations of chlorides may promote stress cracking in equipment operating above 60 °C (Tatnall, 1981).

Tubercles and associated microorganisms are responsible for the formation of differential aeration or concentration cells between the deposit and the surrounding environment. Tubercles restrict percolation of water and as a consequence, are poorly aerated underneath the deposit. Therefore, the area under the tubercle becomes anodic. In addition, iron bacteria which proliferate inside the deposit can cause the oxygen concentration in the immediate vicinity to decrease. The depletion of oxygen at the surface of the tubercle, forms the anaerobic environment necessary for sulfate reducers (Olsen and Szybalski, 1949).

Olsen and Szybalski (1949) suggested that one way of inhibiting corrosion might be to cover the tubercle with a thick protective layer. The protective layer would provide the resistance necessary to decrease the current density at the anode, reducing corrosion. This protective layer may be provided by the addition of lime to change the conditions on the surface of the tubercles favouring the formation of tight layers of protective $CaCO_3$ and carbonate-containing deposits (Olsen and Szybalski, 1949). However, inhibitory chemicals, effective for controlling electrochemical corrosion, may be ineffective in controlling microbial mediated corrosion.

Iron bacteria play only a minor role in the establishment of anaerobic conditions under the tubercle. Their primary role is the formation of the tubercle. Once the tubercle has formed, corrosion proceeds almost independently of the metabolic activity of iron bacteria (Olsen and Szybalski, 1949).

A second group of aerobic intensifying corrosion bacteria are the sulfur oxidizers such as Thiobacillus. The corrosive mechanism of these bacteria is their ability to produce sulfuric acid from the oxidation of inorganic sulfur or elemental sulfur (Bos, 1988). They also oxidize ferrous iron to ferric. These microorganisms thrive in environments characterized by low pH. Sulfur oxidizers often coexist with sulfate reducers. These bacteria have been associated with corrosion of metals involving the transport of acid mine effluents or pipes in contact with acidic soils.

Corrosion in an anaerobic environment is commonly associated with the presence of sulfate-reducing bacteria. In order for these organisms to survive in an oxygen rich environment they must coexist with oxygen scavengers that create the required anaerobic conditions. Simple crevices or inert deposits will not support the growth of sulfate-reducers without the presence of aerobic oxygen scavengers (Tatnall, 1981). For example, anaerobic bacteria have been found within tubercles, where oxygen penetration is limited (Tuovinen et al., 1980).

Anaerobic microorganisms have traditionally been considered the most significant group for causing corrosion. The most common are the sulfate reducers such as the genus Desulfovibrio desulfuricans or Desulfotomaculum. Sulfate reducers use sulfate in a dissimilatry sulfur metabolism to assimilate organic matter. They also use high levels of iron in their cell structure. The by-product, sulfide, then reacts with available hydrogen and iron to form H_2S and FeS (Iverson et al., 1983). It is primarily the production of H_2S which makes these organisms corrosive to metals. Most strains also contain the enzyme hydrogenase which further catalyses the reduction of sulfate by hydrogen (Tatnall, 1981).

The mechanisms by which sulfate reducing bacteria cause corrosion are not completely agreed upon, with many authors suggesting alternative processes (Booth et al., 1962; Mara, 1972). However, several mechanisms have been proposed. These are (Tatnall, 1981):

a. the generation of H_2S which is corrosive to metals;

b. the formation of concentration cells brought about by the anaerobic environment;

c. the favouring of kinetics for metal dissolution by the complexing of metal ions at the surface as insoluble sulfides; and

d. the cathodic depolarization by the enzyme hydrogenase induced reaction of hydrogen with sulfates.

Symptoms of bacteria corrosion are indicated by characteristic deposits. For example, sulfate reducers produce characteristic black deposits of FeS. Iron bacteria produce deposits that are either brown or reddish in colour. The reddish deposits are associated with the species Gallionella. Deposits with a strong yellow colour may be elemental sulfur, produced by species such as Beggiatoa (Tatnall, 1981).

The shape and location of deposits is also indicative of the type of bacterial species involved. Iron bacteria produce tubercles which are hollow and hemispherical. Sulfate reducers generally cause open pitting of stainless steels. On cast iron they generally produce graphitization, whereby the corroded areas are filled with a soft skeleton of graphite (Tatnall, 1981).

Controlling the growth and presence of these organisms is often the only practical course of action. Chlorine is commonly added to potable water for biological control. However, the disinfecting power of chlorinated water for inhibiting microbial activity is limited or ineffective when considering colonized niches. Niches can be crevices, incrustations or tubercles. Effective at the exterior only, the disinfectant does little to affect microbial activity within the niche (AWWA, 1985). For an infested distribution system, control usually requires the removal of deposits supporting microbial colonies. Killing the bacteria, but not removing the deposits will only result in the remaining microorganisms thriving again to cause a reoccurrence of the problem. System flushing is not an effective strategy for preventing the accumulation of microorganisms in the distribution system. However, flushing is useful where excessive growths have occured (Hudson et al., 1983, Geldreich et al., 1972). The large majority of microorganisms present in distribution systems reside in biofilms on pipe walls (Donlan and Pipes, 1988). Increasing the flow velocity can scour the wall surface to reduce the biofilm size and assist in removing the organisms. As well, reported is that increasing the flow velocities will provide a larger disinfectant flux, which may help in microorganism control. Concurrently, a larger flow rate may also provide a higher nutrient flux, which may stimulate growth. Complete mechanical cleaning of the system is usually the only effective approach.

For example, the water works of Hannover found the only way it could control the proliferation of microorganisms in the water distribution system was to remove the incrustations through intense cleaning of the system (AWWA, 1985). In addition to mechanical cleaning of the distribution system, AWWA (1985) recommends for transmission lines, who's lining has dissolved, have a new cement-mortar lining applied. Subsequent application of a cement-mortar greatly reduces the dangers of the temporary redevelopment of bacterial colonies after mechanical cleaning.

2.8 Scale Formation

2.8.1 Protective Properties

The formation of scales on the surfaces of metals serves to protect the metal from further corrosion by inhibiting the transport of such species as dissolved oxygen to the metal's surface (AWWA, 1985). The scale produced and its protective properties will be dependent on the type of metal, the composition of the water at the metal's surface, and the water's biological characteristics. The type of scale deposited on the metal surface will have a direct influence on the metal's corrosion rate. For example, the scales formed from the iron corrosion are ferric hydroxide, ferrous hydroxide, and ferrous carbonate. Ferric hydroxide and ferrous hydroxide produce a scale that is porous and does little to reduce iron corrosion, whereas, ferrous carbonate produces a scale that is much more dense and more protective (Montgomery, 1985; AWWA, 1985).

The most protective scale formed in the case of copper corrosion is tenorite. Tenorite is thermodynamically stable in high pH water. Tenorite is very dense and greatly reduces the transport of oxygen to the cathode surface. However, the stability of tenorite decreases with decreasing pH. For waters of neutral pH and high alkalinity the scale formation is malachite ($Cu(CO_3)^* Cu(OH)_2$). Malachite forms as a metastable species and latter transforms to tenorite (Montgomery, 1985).

Bacteria also influence the quality of corrosion products by acting as a catalyst. For example, sulfate-reducing bacteria in the reduction of sulfate can produce ferrous sulfide. Sulfate reduction leads to components of the corrosion scale which are porous, highly reduced, and easily susceptible to oxidation (AWWA, 1985). Other example reactions as a result of microorganisms acting as the catalyst are:

$$5Fe^{2+} + NO_3^- + 9OH^- \rightarrow 5FeOOH + 0.5N_2 + 2H_2O$$

(denitrifying bacteria)

$$Fe^{2+} + 4Fe + SO_4^{2-} + 4H_2O \rightarrow 4Fe(OH)_2 + FeS$$

(sulfate-reducing bacteria)

The result is the formation of corrosion products such as FeS, $Fe(OH)_2$, and FeOOH which are less protective than coatings of $FeCO_3$.

2.9 Corrosion Rate Measurements

Two methods are used to identify and monitor corrosion. These methods are the weight loss determination method and the electrochemical method.

The weight loss determination method includes the coupon weight-loss method and the pipe insert method. In either case metal coupons or pipe sections are used as test specimens. Using pipe sections, however, is more representative of the pipe exposure conditions. To determine the corrosion rate, test specimens are weighed before and after exposure to the test environment. The amount of corrosion is based on the amount of metal loss for the exposure time and to calculate the corrosion rate the following equation is used:

$$\textbf{Corrosion Rate } (g/m^2\ d) = (W_1 - W_2)/(T)(A)$$

W_1 = overall mass loss (g)
W_2 = mass loss of blank (g)
T = time (days)
A = surface area of metal coupon, does not include the coupon edge area, (m^2)

These types of methods are excellent for measuring uniform corrosion. However, these methods alone can not measure localized corrosion.

The relationship between corrosion rate in grams per square metre per day ($g/(m^2\ d)$) and penetration in mm per year (mmpy) is expressed as follows:

$$\text{mmpy} = g/(m^2\ d) \times 365/D$$

Where D is the density of the metal in kg/m^3. The densities for various metals are:

Metal Type	Density kg/m^3
Steel	7860
Ductile iron	7111
Copper	8920
Zinc (glavinized)	7150

ref: Metals Handbook (1961)

An Alternative method to measure corrosion rate are by electrochemical methods. Electrochemical methods include the methods of electrical resistance and linear polarization resistance. The electrical resistance method is based on the principle that the rate of change of the metal's electrical resistance is directly proportional to its rate of change of its cross sectional area, which in turn is a function of the corrosion rate. The linear polarization resistance method is based on the principle that at low corrosion potentials corrosion rate is essentially a linear function of polarization resistance (Montgomery, 1985).

The advantages to using electrochemical methods are that corrosion rates can be determined instantaneously or over a period of time. Localized corrosion can also be measured.

3.0 Potable Corrosion Inhibitors

3.1 Definition

The definition of an inhibitor, according to the National Association for Corrosion Engineers (N.A.C.E), is a substance which retards corrosion when added to an environment in small concentrations (NACE, 1970). Applied to protect a system used to deliver potable water, the inhibitor must satisfy the following criteria:

a. minimize, to an economically tolerable level, the corrosion damage;

b. not change the water quality to affect the health of the consumer; and

c. not affect taste, odour, and colour of the water.

As a result of these restrictions the choice and use of inhibitors presently available for potable water systems are limited and complex. Most inhibitors used for potable water systems naturally exist in water, and by increasing their concentration may potentially reduce corrosion. Added in small amounts, the concentrations at which these inhibitors are used do not present a health risk to the consumer (AWWA, 1985, 1989).

3.2 Inhibitory Mechanisms of Corrosion Inhibitors

Corrosion inhibitors are categorized into four major groups based on the mechanism by which they reduce corrosion. These categories are; barrier layer formers, neutralizers, scavengers, and miscellaneous types (Dean et al., 1981).

3.2.1 Barrier Layer Formers

Barrier layer formers are corrosion inhibitors which, when deposited on the metal surface, form a barrier layer to interfere with the corrosion reaction(s). These types of inhibitors are further classified into oxidizers, adsorbed layer formers, and conversion layer formers (Dean et al., 1981).

3.2.2 Adsorptive Inhibitors

Adsorptive inhibitors reduce corrosion by adsorbing strongly to form barrier layers over the corroding metal surface to interfere with both anodic and cathodic reactions (AWWA, 1985). Types of adsorptive inhibitors include polar organics such as: acetylenic alcohols, quinoline, aromatic amines, quaternary salts, and various organic sulfur compounds. These inhibitors function as adsorbed layer inhibitors in strong acid solutions (Dean et al., 1981).

Adsorptive inhibitors are not used extensively in potable water. Phosphates and silicates are initially adsorbed onto metal surfaces, but later react to form barrier films (AWWA, 1985).

3.2.3 Oxidizing Inhibitors or Passivators

Passivators reduce corrosion by shifting the electrochemical potential of the corroding metal into a region where a stable, insoluble oxide or hydroxide forms which protects the metal surface. These types of inhibitors are particularly effective in reducing the corrosion of steel and copper based alloys (Dean et al., 1981; AWWA, 1985). As well, they are useful in aqueous solutions of neutral pH. Examples include chromates, nitrates, molybdate, and tungstates. Unfortunately, none of these are acceptable for use in potable water systems. The major advantages of these types of inhibitors are that they are relatively inexpensive, and effective at low concentrations (Dean et al., 1981).

3.2.4 Conversion Layer Formers

Conversion layer formers are inhibitors which form insoluble compounds on the metal surface without relying on the oxidation requirement of passivating inhibitors. These types of inhibitors limit and suppress the cathodic reaction (Dean et al., 1981; AWWA, 1985). Examples include phosphates and silicates, both of which are deposited on the metal's surface to form insoluble metal complexes to inhibit the diffusion of oxygen to the cathode area. Corrosion layer formers are further aided by the presence of divalent cations such as zinc, calcium, or magnesium.

3.2.5 Neutralizers

Neutralizing inhibitors are applicable in the treatment of boiler waters and acidic solutions. Their primary purpose is to reduce the hydrogen ion concentration in the environment to reduce the corrosion process driven by the reduction of hydrogen ions to hydrogen gas. For potable waters, the corrosion process is controlled by the rate at which oxygen is diffused to the metal's surface, and not by the reduction of hydrogen ions.

Examples are pH adjustment chemicals such as sodium carbonate or sodium hydroxide. Neutralizing acidic solutions may also promote the precipitation of insoluble metal complexes by reducing the solubility of metal ions such as calcium, to further reduce corrosion.

3.2.6 Scavengers

Scavengers are inhibitors added to remove or neutralize substances which cause corrosion. This may be achieved by the complete removal of the substance or by chemical reaction to convert it to a substance that is less corrosive. An example of the widely used scavenger is sodium sulfite, added to remove oxygen from the feed water of boilers. An example of an inhibitor used in drinking water is the addition of ammonia to react with free chlorine to form chloramines which are much less corrosive to metals (Ryder and Hoyt, 1977; AWWA, 1985).

3.2.7 Miscellaneous

Miscellaneous inhibitors are chemicals used to inhibit scale or biological growth. Scale inhibitors function by interfering with the normal crystal growth to form soft non-adherent precipitates (Dean et al., 1981), or to sequestor ions to remain in solution as soluble metal complexes. This prevents the deposition of insoluble metal salts which can cause corrosion by formation of concentration cells.

Inhibitors to control biological growth are biocides added to control corrosion and fouling of pipes which result from excessive biological growth.

3.3 Types of Inhibitors

3.3.1 Lime

Lime is the most widely applied chemical to potable water systems for corrosion control. Corrosion reduction from the application of lime is achieved mostly when calcium precipitates as $CaCO_3$, forming a protective coating on the metal's surface. For $CaCO_3$ precipitation to occur, the water in question must be either saturated or oversaturated with respect to calcium carbonate. The degree of oversaturation is important. Excess deposition of $CaCO_3$ is detrimental, for it decreases the cross-sectional area of the pipe to reduce the pipe's hydraulic capacity. Ideally, after the initial protective coating has formed in the system, efforts should be made to refurbish only the $CaCO_3$ which is lost from the process of erosion. To predict the water's tendency to precipitate $CaCO_3$, the following $CaCO_3$ based indices can be used; Langelier Saturation index, Ryznar index, Aggressive Index, or the Caldwell-Lawrence diagram. These indices are not measurements of corrosivity. Rather they are useful only for predicting the water's tendency to precipitate $CaCO_3$. Caution is advised when using these indices as their predictions can sometimes be misleading. However, they can be a valuable monitoring tool when used in conjunction with other direct or indirect corrosion monitoring methods.

Operational guidelines to the application of lime is that the water should be brought to the oversaturated condition just prior to entering the distribution system. In addition, chemical conditioning with lime should follow both filtration and chlorination. Chlorinating after chemically conditioning the water will reduce the water's precipitation potential for $CaCO_3$ (Merrill and Sanks, 1978).

The protective coating formed from the deposition of $CaCO_3$ consists of a complex mixture of $CaCO_3$ and metallic corrosion products such as $FeCO_3$, $Fe(OH)_2$ and $ZnCO_3$. Field inspections show an effective coating results only when $CaCO_3$ becomes intermixed with corrosion products and the velocity of the system is in excess of 0.6 m/s (Haase, 1952). In addition, the $CaCO_3$ coating must be uniform and tenacious to be protective. If not, conditions for localized corrosion can develop. Merrill and Sanks (1978) suggested that a water offering good protection by the potential to deposit $CaCO_3$ be oversaturated with $CaCO_3$ in the range of 4 to 10 mg/L as $CaCO_3$ and both calcium and alkalinity values be at least 40 mg/L as $CaCO_3$.

McCauley (1960) showed that the quality of the protective coating is improved by immediately quenching lime with carbon dioxide, and in doing so, a positively charged colloidal $CaCO_3$ precipitate is produced. This colloidal precipitate is smaller and forms a more tenacious coating than would $CaCO_3$ crystals of no charge.

The addition of lime alone to very soft, low alkalinity waters may never result in calcium carbonate saturation (AWWA, 1985). Small additions of lime to waters with low buffer capacity will result in large changes to pH ($pH > 11$), which will exceed the maximum imposed for potable waters. To economically supersaturate soft, low alkalinity waters with $CaCO_3$ may require adding, in addition to lime and carbon dioxide, alkalinity by itself. The addition of these three chemicals may condition the water to precipitate $CaCO_3$ without having to add large additions of lime. Adding large amounts of lime is impractical and uneconomical.

Adjustment of the Langelier Saturation Index (LSI) to slightly positive value has been a common approach to produce a water that is protective. However, good protection with calcium carbonate incorporated into corrosion scales has been achieved even though the LSI is slightly negative. Hydroxide production at the cathodic sites can locally increase the pH and promote the precipitation of $CaCO_3$, even though the bulk solution is undersaturated (AWWA, 1985). Although, this is not true for waters taht are greatly undersaturated with respect to $CaCO_3$. However, depending on the type of metal to be protected, protection from lime addition may occur as a result of other water quality changes than from the precipitation of $CaCO_3$. Generally, waters with a scaling tendency are usually noncorrosive toward iron and copper (AWWA, 1989).

3.3.2 Polyphosphate

Polyphosphate's ability to reduce corrosion is achieved only when polyphosphate is precipitated as an insoluble metal phosphate compound onto the metal's surface (AWWA, 1989). The precipitation of this compound onto the metal's surface serves to limit and suppress the cathodic reaction in the electrochemical process. This type of corrosion control results from the formation of protective scales on the surface of the metal. The layer of insoluble metal phosphate that forms has some permeability so the corrosion reaction will not be totally eliminated-only reduced to a more manageable level (AWWA, 1989). Polyphosphate inhibitors are useful to control corrosion from oxygen attack, but they are not applicable to controlling corrosion from acid or anaerobic attack (Larson, 1957).

Corrosion reduction by polyphosphates is further aided by the presence of divalent cations such as: zinc, calcium and magnesium. Polyphosphate reacts with and precipitates as iron, calcium and magnesium salts (AWWA, 1989). Phosphate will also combine with oxygen to form a crystalline lattice structure with precipitated metal phosphates (Nancollas, 1983). Hatch (1969) noted that the critical factor for corrosion control is the calcium to phosphate ratio. Sufficient calcium is required to ensure the formation of the polyphosphate salt. Hatch also stated that the minimum calcium to sodium polyphosphate weight ratio (Ca/PO_4) as being 1:5 for the formation of protective films on metal surfaces over a wide range of polyphosphate concentrations, the lowest being 1.0 mg/L when a adequate Ca/PO_4 ratio is maintained.

Clearly established is polyphosphate's ability to combine with and sequester dissolved ferrous ions into stable dissolved complexes. This prevents ferrous ions from further oxidizing to ferric forms and forming rust-coloured insoluble hydroxides (Montgomery, 1985). Consequently, polyphosphates may be useful in preventing the problem of "red water." However, polyphosphates at high concentrations, though unable to reduce ferric oxide forms, can have a softening effect on previously established corrosion scales to cause the problem of "red water."

Little information is known concerning the mechanism for the formation and dissolution of polyphosphate salts. However, Nancollas (1979) showed that the crystallization of most salts is controlled by surface reactions and scale formation and will more likely occur for corroded surfaces. Hatch and Rice (1939) reported polyphosphate is adsorbed onto surfaces of old metal salts or oxides. Therefore, old deposits in a distribution system will tend to retard establishment of protection. These deposits will compete for the polyphosphate, thereby decreasing the supply available for protective film formation. Therefore, the application of polyphosphates to a distribution system experiencing corrosion problems will cause inhibitor consumption to be highest in the early stages of treatment. This problem can be alleviated by an initial high polyphosphate feed which is known as pretreatment. However, the application of polyphosphate to a distribution system experiencing severe corrosion problems can cause the problem known as "red water". Polyphosphate at high concentrations causes a softening of corrosion scales, which from turbulent conditions inside the pipe can be resuspended to affect water colour, and introduce scale deposits. To avoid this problem may require the distribution system be cleaned if corrosion scales susceptible to the chemical's adverse effects are present.

Preconditioning with polyphosphate has been done during and after mechanical cleaning of the distribution system. Hatch (1973) recommended the following pretreatment program;

a. Use a polyphosphate dosage of 25 mg/L as PO_4 during cleaning.

b. After cleaning use a 20 to 40 mg/L as PO_4 of polyphosphate for one day.

c. A stepwise reduction over one week to 10 mg/L as PO_4.

d. A similar stepwise reduction over one month to 5 mg/L as PO_4.

e. Finally, a reduction over one month to the maintenance dosage of 1 to 2 mg/L as PO_4.

Hatch (1955) suggested that the optimum pH range for the application of polyphosphate is between pH 5 to 7. Deterioration of the inhibitor's performance becomes quite pronounced above pH 7.4. However, the presence of bimetallic ions can increase the effective range of inhibition to pH 7.5 to 8.0 (AWWA, 1989).

Hatch (1952) discovered that the protective film provided by polyphosphate at the cathode area was the result of electrodeposition. The current generated in the metal from corrosion attracts the deposition of positively charged colloidal metal phosphate compounds to plate out onto the cathode area. As this protective film increases in both thickness and density, the current between the cathode and anode area decreases, slowing the rate of deposition. This physical characteristic causes the protective film to be self-limiting. If treatment with polyphosphate is stopped the film deposited becomes less protective.

Phosphate inhibitors have been demonstrated as much more effective on iron than on less active metals such as copper. This is because normally, less active metals show insufficient local cell activity to generate the current necessary for deposition of the polyphosphate film. Copper is not coated when exposed alone to polyphosphate treated water. However, copper is coated readily when it constitutes the cathode of a galvanic couple.

The use of polyphosphates is not recommended to control lead solubility (Hettiaratchi and Smith, 1990). Schock (AWWA, 1985) noted a number of controversies related to the use of polyphosphates in lead solubility control. He pointed to some research which found that polyphosphates were not only effective in reducing lead levels, but could actually increase lead levels by complication and solubilization of protective films on the pipe. The aqueous chemistry of lead polyphosphate complexes is largely unknown, and until a clear understanding of the fundamental mechanisms is obtained, the use of polyphosphate to control lead solubility is not recommended.

Phosphorus is an essential nutrient for the growth of algae and other biological organisms. The concentration of phosphorus necessary to support an algae bloom is 0.005 to 0.05 mg/L as P (Metcalf & Eddy, 1979). Bacteria also require phosphorus to support metabolic activities in a ratio of about 1 part phosphorus to 100 parts carbon (Metcalf & Eddy, 1979). In tests done by Ryder (1978) on Seattle's water system, he discovered inhibitor dosages of 1 to 2 mg/L of both sodium hexametaphosphate and zinc orthophosphate stimulated algae growth significantly (AWWA, 1985). Therefore, it is appropriate to restrict the dosing of water with phosphate inhibitors at concentrations as low as possible. Also, it is desirable when using phosphate inhibitors to maintain an adequate residual chlorine concentration throughout the entire distribution system to minimize post treatment biological growth (Ryder, 1980).

Polyphosphates undergo hydrolysis in aqueous solutions to revert to orthophosphates due to elevated temperatures or for long contact times. For water temperatures typical of potable waters the rate of hydrolysis will be quite slow (Metcalf & Eddy, 1979). Orthophosphate is known for stimulating algae growth in open reservoirs (AWWA, 1989).

The discharge of wastewaters containing phosphorus can also potentially serve to pollute the receiving body of water. Phosphorus removal, by a normal biological secondary treatment processes is approximately 25 to 40 percent (AWWA, 1985). Advanced waste treatment processes are needed if phosphorus in wastewater effluents is to be less than 1.0 mg/L.

3.3.3 pH Adjustment Chemicals

Sodium hydroxide and sodium carbonate are examples of pH adjustment chemicals. These chemicals reduce corrosion by the inhibitory process known as neutralization or by passivation. As neutralizers, pH adjustment chemicals are effective for potable water systems suffering from acid corrosion as a result of low pH water. As passivators, the ability of pH adjustment chemicals to inhibit corrosion is dependent on the metal type and the pH range in which the chemicals are used. Corrosion inhibition from passivation is achieved only when the pH of the water has been elevated to shift the electrochemical potential of the metal into a region where a stable insoluble oxide or hydroxide film forms to protect the metal's surface.

The application of either sodium carbonate or sodium hydroxide to potable waters to inhibit corrosion of ductile iron by the process of passivation is usually impractical, due to the pH restriction (maximum pH 8.5) imposed by the Guidelines for Canadian Drinking Water Quality (GCDWQ,1987). Rozenfeld (1972), showed iron corrosion between the pH range of 4 to 10 to be independent of pH. He showed iron corrosion as being dependent on the rate of oxygen transfer to the metal's surface. Only above the pH value of 10, will there be a noticeable decrease in the corrosion of iron. Studies done by Eliassen et al. (1953) and Uhlig (1971) showed similar results in which pH variation over the range of 6 to 9.5 during short-term corrosion tests of clean steel specimens had little effect in reducing corrosion. To use pH adjustment chemicals alone, for reducing corrosion of iron would be ineffective unless the water is of sufficient hardness that pH adjustment would promote the deposition of a protective coating of $CaCO_3$. Thus ferrous metals are not well protected in low mineralized waters by pH adjustment unless the pH is above 8.5, a maximum imposed for potable waters (AWWA, 1985).

Known is that pH will have an effect on secondary reactions in the oxidation of ferrous iron (AWWA, 1985). Depending on the pH and alkalinity of the water, ferrous iron will undergo secondary reactions to form either of the following types of corrosion products: FeOOH(s) (geothite), or $FeCO_{3(s)}$, or $Fe(OH)_{2(s)}$. The type of scale deposited on the metal's surface will have a direct effect on the quality of formation scale, which influences corrosion (AWWA, 1985). For example, the deposition of the scale FeOOH (geothite) produces a scale layer which is very porous and offers little resistance to oxygen diffusion. In comparison, a layer of $FeCO_3$ (siderite) scale forms a dense layer with good resistance to oxygen diffusion. (AWWA, 1985). Of these two types of scales, $FeCO_3$ (siderite) produces a scale which is more protective. However, the FeOOH (geothite) is likely to form for low alkalinity waters, as is the case for Yellowknife's supply water.

pH adjustment chemicals can be beneficial depending on the type of metal to be protected. For example, copper corrosion is very pH dependent in soft, low mineralized waters (AWWA, 1989). The tendency is for copper corrosion to decrease as pH increases.

The addition of sodium hydroxide or sodium carbonate increases the water's sodium concentration. AWWA (1985) suggests that large additions of sodium be avoided and that the amount added should be limited so as not to increase the water's background concentration by more than 20%. The reasoning is in regard to the health concern sodium intake poses. Sodium intake has been positively correlated with the incidence of cardiovascular disease (AWWA, 1985). The GCDWQ (1989) does not recommend a limit for sodium. Suggested instead, is that sodium be included in routine monitoring programs, since the levels may be of interest to authorities who wish to prescribe sodium restricted diets for patients.

A case study of Seattle's corrosion problem by Kennedy Engineers (1978), identified the corrosion of the consumer's plumbing, primarily copper, as the most significant. Soft, low pH water in Seattle's distribution system, combined with low buffer intensity, free chlorine residual, and hydrofluosilicic acid, correlated with the excessive corrosion of copper piping. It was shown that adding small amounts of lime and sodium carbonate to increase the pH from 6.0 to 8.0 reduced both copper and lead corrosion. In addition, tap water samples collected showed dramatic reductions in concentrations of lead and copper. However, the effects, if any, on galvanized pipe corrosion were not determined (Kennedy Engineers, 1978).

pH adjustment of Pinellas County, Florida's, water supply was tried as a means of reducing the corrosion of copper piping used in home plumbing. It was found that increasing the pH of the supply water to 7.9, using sodium hydroxide, reduced the carbon dioxide concentration from 8.0 mg/L to 3.0 mg/L. The effect of these water quality changes was that the water's copper concentration decreased from 1.5 mg/L to 0.33 mg/L. Although, increasing the pH caused excessive scaling of pipes and pumps near the point of lime softening.

3.3.4 Sodium Silicate

Protection by silicates occurs when a thin layer of silica gel is deposited over a layer of corroded metal. Silicates are deposited to form a metal silicate barrier on top of and interlatticed with the metal hydroxide structure (AWWA, 1989). Lehrman and Shuldener (1951) demonstrated silica is not deposited on clean iron. It is necessary first that a layer of iron oxide be present before the protective silica film is formed. Film formation is slow, with some estimating between 22 days (Speller, 1924) to about one month before maximum protection is achieved (AWWA, 1985).

A proposed mechanism for film formation, is negatively charged silica species interact at the anodic sites to form a silica gel. This silica gel combined with the metal oxides forms the protective film. The film is a double layer, with the bottom layer consisting of metal oxides and the top layer consisting of amorphous silicate. The amorphous silicate acts as a passivating inhibitor and increases to eventually block both the cathode and anode sites. Silica films will gradually break down with time and protection will cease if the application of silicate is stopped. Similar to polyphosphate, silica films are self-limiting.

Soft waters of low pH (<7) and high oxygen content (>6 mg/L) are most likely to benefit from the addition of silicates (AWWA, 1989). Lane et al. (1973) stated that protection using silicate is achieved for dose concentrations varying from 4 to 12 mg/L as SiO_2; although, higher silicate concentrations may be necessary for waters with high concentrations of hardness, chlorides, and dissolved solids. In Seattle, Kennedy Engineers (1978) found that silicate addition for the concentration range 10 to 12 mg/L as SiO_2 at pH 8.0 reduced the corrosion of both copper and steel, but the effects were not significantly different from pH change alone. The addition of sodium silicate increases pH for large dosages and this appears to be the principal benefit to reducing copper corrosion. Silicate, however, is not effective in low velocity water conditions.

Silicates can stimulate the growth of particular biological species in low mineralized waters. For example, the use of silicate at a dosage of 4 mg/L as SiO_2 in Seattle's water system increased the growth of the diatom Synedra (AWWA, 1985).

4.0 Metal Coupons

4.1 Materials Used

Metal coupons were made from distribution material supplied by the City of Yellowknife. The materials used were: 150 mm diameter, cement-lined ductile iron and 25 mm diameter, type K, copper piping.

4.2 Preparation of Coupons

The distribution piping material was cut and machined to make 50 mm by 25 mm size coupons. In making the ductile iron coupons, both the inside cement and outside tar linings were removed and the coupon's edges epoxied. Ductile iron coupons were not flattened as to avoid introducing stress into the metal.

Removing the cement lining from the ductile iron pipe required cutting the pipe into 50 mm ring lengths. A 6 lb jack hammer with a flat head bit was used to break the cement lining from the pipe. Once the cement lining had been removed, approximately 1.5 mm of metal was milled from both the inner and outer surface of the pipe rings. A water based coolent was used at all times when cutting, milling, or drilling the test specimens. After the pipe rings were milled, a liquid cooled band saw was used to cut the rings into 50 mm by 25 mm metal coupons.

A similar procedure was used for construction of the copper coupons. With no protective linings to remove, copper pipe sections were cut into 50 mm ring lengths, and then into 50 mm by 25 mm size coupons, using a liquid cooled band saw. Copper is a soft, ductile metal which allowed metal coupons to be flattened using a vice. Special attention was given, so as to not indent or mark the surface of the coupon when flattening. Coupons were then lightly sanded using grade 600 sand paper. The purpose of sanding the surfaces of copper coupons was to obtain a uniform surface texture. Coupon edges were not epoxied, as experience showed that the epoxy would not adequately adhere to the metal surface.

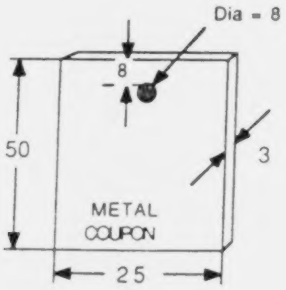
In addition, a 3.5 mm diameter hole was drilled approximately 6.4 mm from the top edge of each coupon type (Figure 4.2.1). This was to allow hanging of the metal coupons using PVC hanging rods.

4.3 Identification and Measuring of Coupons

Metal coupons were not stamped to avoid introducing localized stress into the metal. Instead, Teflon tags with the serial number etched on to the tag were taped to the PV. rod from which the coupon was hung (Figure 4.3.1). To measure the metal coupons a dial vernier with an precision of + / - 0.025 mm, was used.

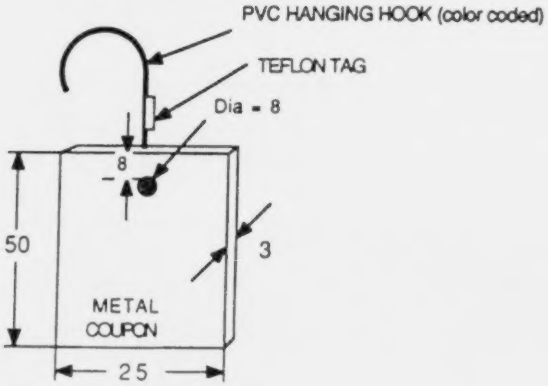
To measure the ductile iron coupons, a somewhat different procedure was used. To measure the curvature of the coupon a piece of

Figure 4.2.1
Dimensions of a Typical Metal Coupon


Dia = 8
8
50
3
METAL
COUPON
25

(ALL DIMENSIONS IN MM)

Figure 4.3.1
Method used for Identifying and Hanging Metal Coupons


PVC HANGING HOOK (color coded)
TEFLON TAG
Dia = 8
8
50
3
METAL
COUPON
25

(ALL DIMENSIONS IN MM)

labelling tape was laid across the curved surface and marked at the edges. After which, the tape was removed and laid flat on a table where the distance was measured using the dial vernier. In measuring the same coupon ten times the following may be concluded in the accuracy of the measuring procedure:

a. average length was 50.140 mm with a standard deviation of 0.019 mm;

b. average inner surface width was 35.738 mm with a standard deviation of 0.034 mm; and

c. average outer surface width was 37.287 mm with a standard deviation of 0.049 mm;

4.4 Processing of Coupons

The procedure used to clean the metal coupons was identical to that used by Millette (1985), which is a modification of the method developed by Larson and King (1954). To clean the metal coupons required the coupons be dipped successively into the nine washing baths, as listed in Table 4.4.1. Upon completion of this, metal coupons were stored in a dessicator for a minimum of 12 hours before weighing and usage.

In the cleaning operation, coupons were strung using a wire cable as shown in Figures 4.4.1 & 4.4.2. To ensure good contact between the metal and the cleaning solutions, Teflon spacers were inserted in between coupons. Special precautions were taken not to touch the cleaned coupons and to store the coupons independently from each other.

Table 4.4.1
Cleaning Procedure for Metal Coupons

Bath #	Solution	Exposure Time (minutes)	Remarks
1	Carbon Tetrachloride	3	removes grease and oils
2	2.5 % Nitric & HCl acids	2	acid treatment to remove metal oxides
3	Concentrated HCl acid	1	acid treatment to remove metal oxides
4	Distilled Water	2	rinse
5	Sodium Carbonate (1N)	2	acid neutralized by a weak base
6	Distilled Water	2	rinse
7	Distilled Water	2	rinse
8	Acetone	2	removal of water
9	Acetone	2	removal of water

Figure 4.4.1
Cleaning Arrangement of Metal Coupons

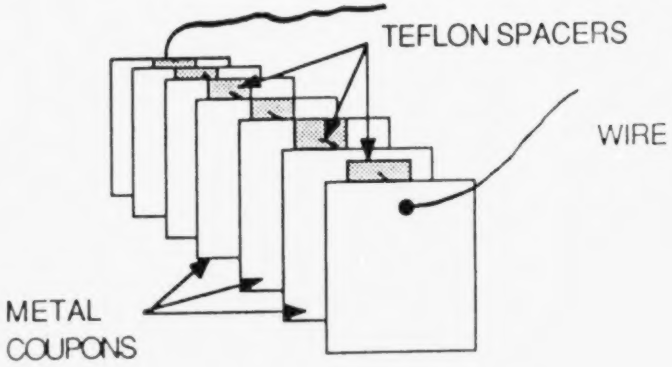
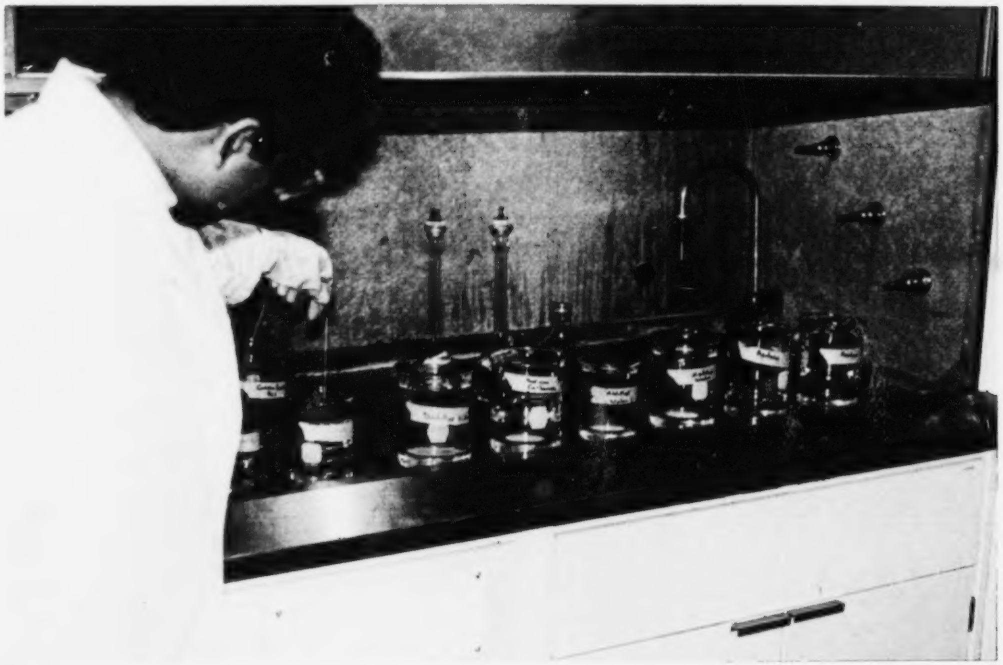

TEFLON SPACERS
WIRE
METAL
COUPONS

Figure 4.4.2
Cleaning of Metal Coupons



4.5 Procedure for Weighing Coupons

Metal coupons were individually weighed after being cleaned and stored in a desiccator for a time period of 12 hours. Latex gloves and metal thongs were used for when handling the coupons. The weigh scale was calibrated before use. The type of weigh scale used was the Mettler AE 163 with a precision of +/-0.0001g.

4.6 Handling of Blank Coupons

To estimate the amount of metal, not corrosion products, removed by the coupon cleaning process required coupons, not exposed to the test environment, to be cleaned along with the test coupons. These metal coupons, referred to as blanks, were stored at all times in a non-corrosive environment, namely a desiccator. The blank ductile iron metal coupons were identical to the test coupons used. That is, they were of the same size and the edges were epoxied. Similarly, the blank copper metal coupons were also identical to the test coupons used.

4.7 Corrosion Rate Calculation

Corrosion measurement was by the weight loss determination method using metal coupons. This method is relatively easy and inexpensive to perform and can yield useful general corrosion rate data. The measurements are not instantaneous and therefore the experiments are time consuming. The procedure provides direct information of the amount of metal consumed by corrosion over a given period of time. Disadvantages are that the method cannot accurately provide information on possible variations in corrosion rate at different time intervals for the test period. That is, weight loss measurements alone cannot distinguish between uniform and localized corrosion. As well, metal coupons are less representative of actual pipe exposure conditions, scale formation, and the action of inhibitors, as compared to using pipe inserts (AWWA, 1985, 1989).

The average corrosion rates were calculated using the following equation;

$$\textbf{Corrosion Rate } (g/m^2\ d) = (W_1 - W_2)/(T)(A)$$

W_1 = overall mass loss (g)
W_2 = mass loss of blank (g)
T = time (days)
A = surface area of metal coupon, does not include the coupon edge area, (m^2)

The weight loss measurements required the sensitive weighing of coupons before and after tests. Cleaned, along with the corroded coupons, were blank coupons not exposed to the test environment. These blank coupons served to determine the amount of clean metal, not corrosion products, that was removed by the cleaning process. This amount, known as the blank loss (W_2), was subtracted from the overall mass loss (W_1).

The surface area in the corrosion rate equation does not include the coupon edge area. For ductile iron coupons, the edges were coated with epoxy to allow for this area to be neglected. For copper coupons, the edge area was small with respect to the total surface area and was therefore neglected.

4.8 Analytical Procedures

Unless otherwise specified, all analytical tests were preformed according to Standard Methods for the Examination of Water and Wastewater (AWWA-APHA-WPCF, 1989).

4.8.1 Alkalinity

Alkalinity was determined according to section 2320 B of Standard Methods (AWWA-AHPA-WPCF, 1989). Analysis of samples for an alkalinity of less than 20 mg/L as $CaCO_3$ was by the low alkalinity test. As well, tests were performed for a sample temperature range of 5 and 7 °C.

The total alkalinity of a solution is defined as the amount of acid required per litre to lower the pH to about 4.3. Mathematically, alkalinity is expressed by the following relationship:

$$\text{Total Alkalinity} = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+]$$

In drinking water, alkalinity is comprised mostly of carbonates and bicarbonates.

No general statement can be made concerning the precision of these tests, given the large variation in sample characteristics and the method being subject to relatively large operator error in accurately distinguishing the color changes for the indicators. However, in the range of 10 to 500 mg/L, when the alkalinity is due entirely to carbonates or bicarbonates, a standard deviation of 1 mg/L as $CaCO_3$ can be achieved (AWWA-AHPA-WPCF, 1989).

4.8.2 Chloride

Chloride determination was by the Automated Ferricyanide Method (section 4500-Cl^- E, AWWA-AHPA-WPCF, 1989). Chloride analysis was performed by Norwest Labs, Edmonton, Alberta. The test has a relative accuracy of +/- 0.01 mg/L as Cl^-.

4.8.3 Chlorine Residual

Chlorine residual determination was by the DPD colorimetric method (section 4500-Cl G, AWWA-AHPA-WPCF, 1989), using the Bausch and Lomb spectrophotometer 20, adjusted to the wave length setting 515 nm. Potassium permanganate standards of 1 to 4 mg/L were used to derive the standard curves.

4.8.4 Dissolved Oxygen

Dissolved oxygen was analyzed using the Azide modification of the iodometric method, by section 4500-O C of Standard Methods (AWWA-AHPA-WPCF, 1989). The iodometric test remains the most precise and reliable method for measuring dissolved oxygen. An experienced analyst can measure dissolved oxygen concentrations with a precision of +/- 50 ug/L, using the visual end-point detection method.

Dissolved oxygen was analyzed prior to changing the experimental water. A 203 mL aliquot sample was used and titrated with 0.025 N thiosulfate.

4.8.5 pH

To measure pH, the Fisher accumet model 805 pH meter was used. The Fisher accumet model 805 pH meter has a relative accuracy of +/- 0.01 pH.

The basic principle of the electrometric pH is the determination of the activity of the hydrogen ions by potentiometric measurement using a single glass electrode. The activity of the hydrogen ion is dependent on temperature and the pH metre must be calibrated according to the temperature of the sample. The pH metre was calibrated daily before use.

4.8.6 Sulfate

Sulfate determination was by the turbidimetric method, section 4500-SO42- E of Standard Methods (AWWA-AHPA-WPCF, 1989), using the HACH 2100A turbidimeter. Samples were analyzed close to room temperature, as was done in the preparation of the standard curves.

4.8.7 Temperature

Temperature was measured using a standard celsius thermometer. Temperature measurements were taken prior to the changing of the experimental water and prior to performing the analytical tests.

4.8.8 Total Hardness

Total hardness analysis was by the EDTA titrimetric method, section 2340 C of Standard Methods (AWWA-AHPA-WPCF, 1989). Total hardness is primarily the sum of the calcium and magnesium concentrations and is expressed as mg/L as $CaCO_3$.

Prior to performing hardness tests, samples were allowed to warm from 5 °C to almost room temperature. Sample sizes were 50 mL. The EDTA titrimetric method has a relative standard deviation of 2.9 % and a relative percent error of 0.8 %.

4.8.9 Turbidity

The method used to measure turbidity was the Nephelometric method, section 2130 B of Standard Methods (AWWA-AHPA-WPCF, 1989). The instrument was the HIACH model 2100A turbidimeter with a sensitivity of 0.02 NTU.

4.8.10 Metal Analysis

Cation analysis was by inductively coupled argon plasma spectrometry on a JY 70 ICP Simultaneous/Sequential spectrometer. Samples were analyzed for the following cations: copper, iron, sodium, magnesium, silicon and calcium. Tests were performed by Norwest Labs, Edmonton, Alberta. Samples were preserved with nitric acid at the time of sampling.

Table 4.8.10.1 lists the detection limits for each of the cations tested.

Table 4.8.10.1
Minimum Detection Limits for Each Cation

Cation Type	Minimum Detection Limit (mg/L)
Calcium	0.1
Copper	0.01
Magnesium	0.05
Iron	0.02
Silicon	0.05
Sodium	1.0

Scource: Norwest Labs, Edmonton, AB

5.0 Phase 1: Yellowknife In-situ Corrosion Study

5.1 Objective

The objective of the Yellowknife in-situ corrosion study was to determine the long term average corrosion rates of ductile iron and copper for exposure to the untreated and treated supply water. In addition, the study was to assess the severity of Yellowknife's corrosion problem by comparison to other communities.

5.2 Methodology

5.2.1 Apparatus Set-up

In-situ corrosion tests were performed in Yellowknife in the distribution pumphouses No.'s 2 and 4. The apparatus set-up used was common to both pumphouses and consisted of connecting parallel with the City's main water distribution line, a constant head tank and two coupon holding tanks. Figure 5.2.1.1 schematically illustrates the apparatus set-up. Ductile iron and copper coupons were housed separately to avoid the problem of galvanic corrosion.

The constant head tank and coupon holding tanks were constructed of 6.4 mm thick Plexiglas and all hose connections were of a non-metallic material such as P.V.C. Figure 5.2.1.2 illustrates a detailed drawing of the coupon holding apparatus.

Test specimens were exposed to an average flow velocity of 0.001 m/s. The duration of the tests was approximately 6 months. Metal

Figure 5.2.1.1
Cross Sectional View of the Apparatus Set-up Used
in the Yellowknife In-situ Corrosion Study

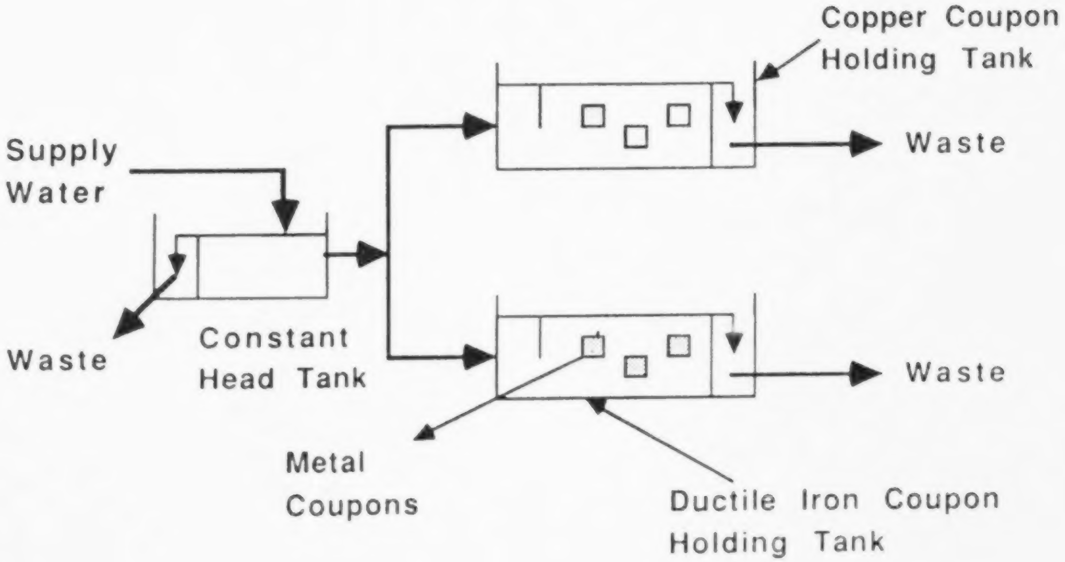
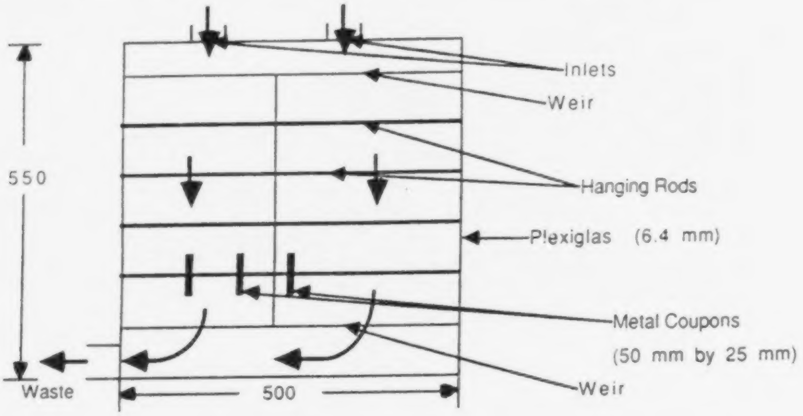
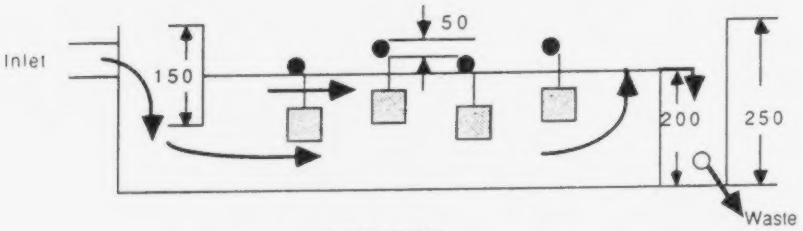

Copper Coupon
Holding Tank
Supply
Water
Waste
Waste
Constant
Head Tank
Waste
Metal
Coupons
Ductile Iron Coupon
Holding Tank

Figure 5.2.1.2
Detailed Drawing of the Metal Coupon Holding Apparatus


Inlets
Weir
Hanging Rods
Plexiglas (6.4 mm)
Metal Coupons
(50 mm by 25 mm)
Weir
550
Waste
500

TOP VIEW


Inlet
150
50
200
250
Waste

SIDE VIEW

All Dimensions mm

coupons were immersed in accordance to section 3.1.4. The depth at which coupons were immersed was 50 and 100 mm below the water surface.

In pumphouse 2, test specimens were exposed to the untreated water (Figures 5.2.1.3 and 5.2.1.4). In pumphouse 4, test specimens were exposed to the treated water (Figures 5.2.1.5 and 5.2.1.6). The purpose of this was to determine the effect on corrosion of treatment of the water from the addition of hydrofluosilicic acid, chlorine and, during the winter, heat.

5.3 Handling of Coupons

Attached as an appendix (Appendix F) is the coupon handling instructions for the removal and shipment of coupons. With the assistance of UMA Engineering Ltd., Yellowknife, metal coupons were removed on a weekly basis for the first month and later every month. Coupons removed were thoroughly dried, wrapped in Saran wrap, and immediately couriered to the University of Alberta for processing. The time delay before processing of samples averaged 3 days. However, due to uncontrolled circumstances longer times were experienced. According ASTM Standard Test Methods (1986) the allowable time before processing of coupons should not exceed 7 days.

Preliminary investigation into the handling of samples showed that test specimens not properly dried, continued to corrode during shippment. However, if properly dried, the corrosion rates were not significantly different than if the samples were immediately analyzed (see Appendix G).

Figure 5.2.1.3
Experimental Apparatus
Pumphouse No. 2, Yellowknife, N.W.T.

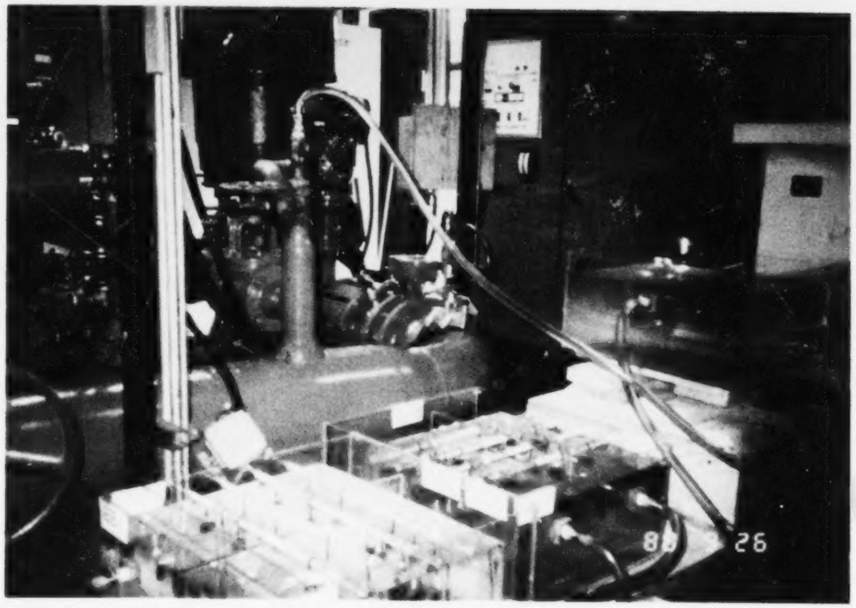


Figure 5.2.1.4
Experimental Apparatus
Pumphouse No. 2, Yellowknife, N.W.T.

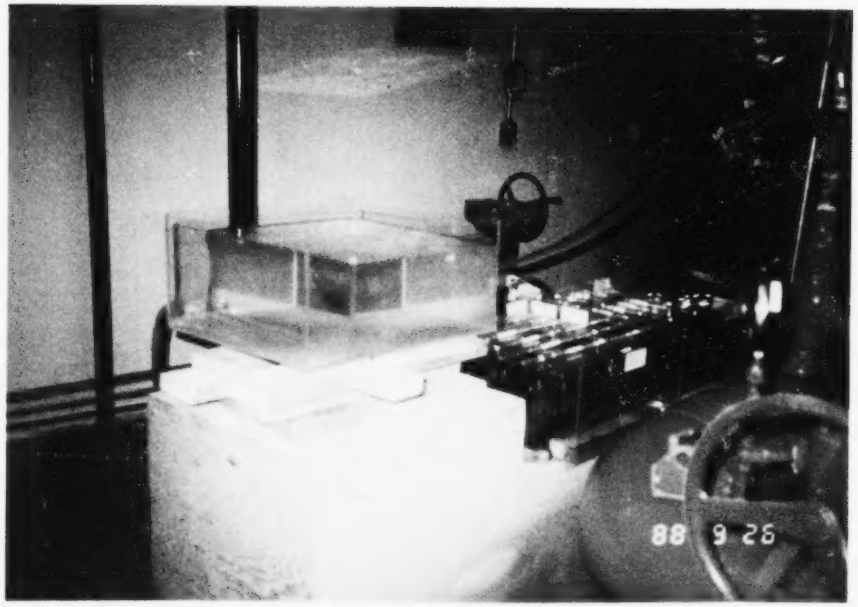
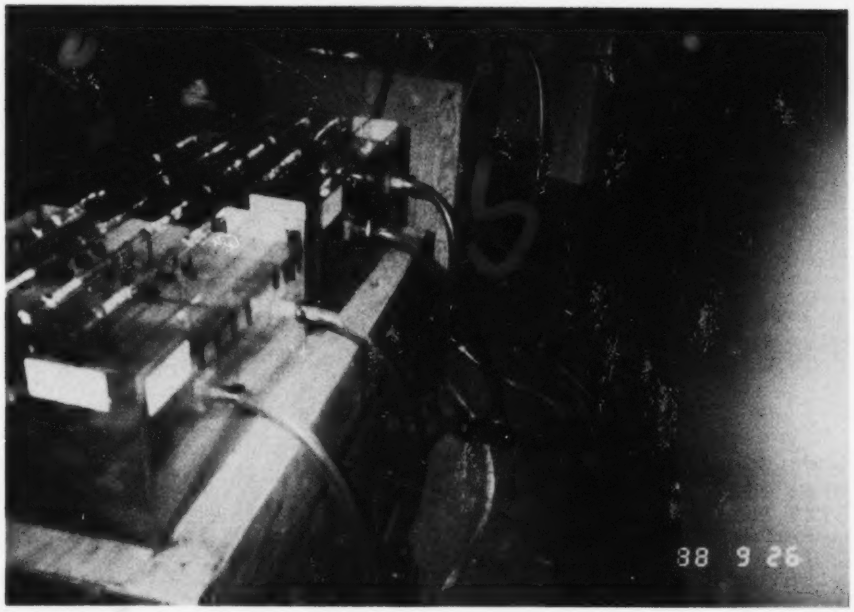


Figure 5.2.1.5
Experimental Apparatus
Pumphouse No. 4, Yellowknife, N.W.T.



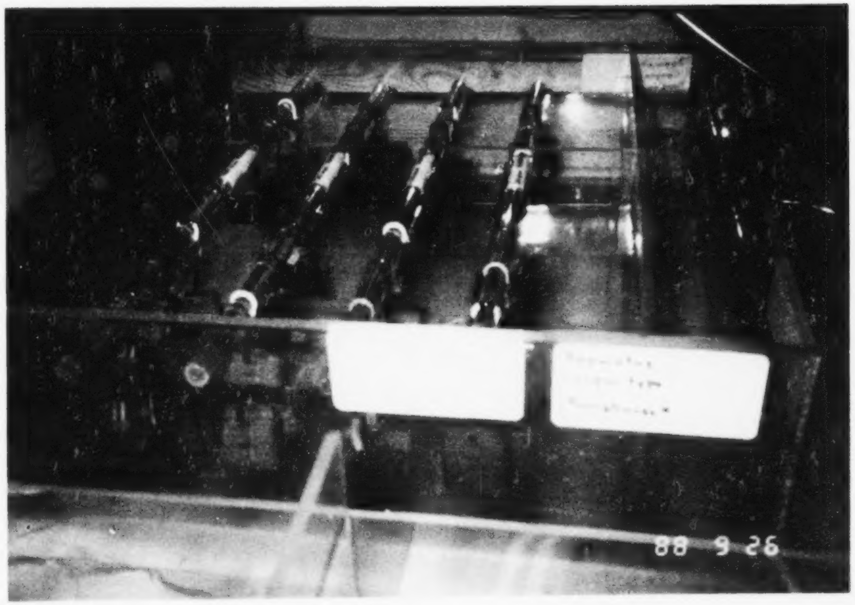


Figure 5.2.1.6
Experimental Apparatus
Pumphouse No. 4, Yellowknife, N.W.T.

5.4 Experimental Schedule

5.4.1 Copper Experiments

Figures 5.4.1.1 and 5.4.1.2 are the experimental schedules for the removal of copper coupons exposed to the raw and treated supply water. Sample sets consisted of three coupons each and were removed weekly for the first month and later every month. The duration of the tests was approximately 123 days.

5.4.2 Ductile Iron Experiments

Figures 5.4.2.1 and 5.4.2.2 are the experimental schedules for the removal of ductile iron coupons exposed to the raw and treated supply water. Sample sets consisted of three coupons each and were removed weekly for the first month and later every month. The duration of the tests was approximately 177 days for exposure to the raw water and 155 days for exposure to the treated water.

Figure 5.4.1.1
Experimental Schedule: Copper Coupons Exposed to the Untreated Water (Pumphouse No. 2)

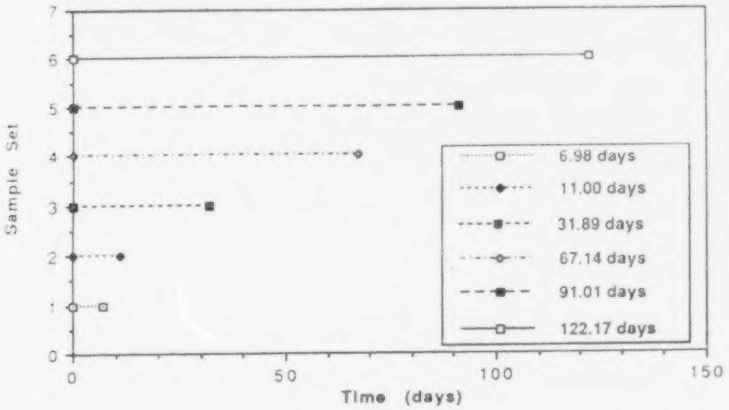


Figure 5.4.1.2
Experimental Schedule: Copper Coupons Exposed to the Treated Water (Pumphouse No. 4)

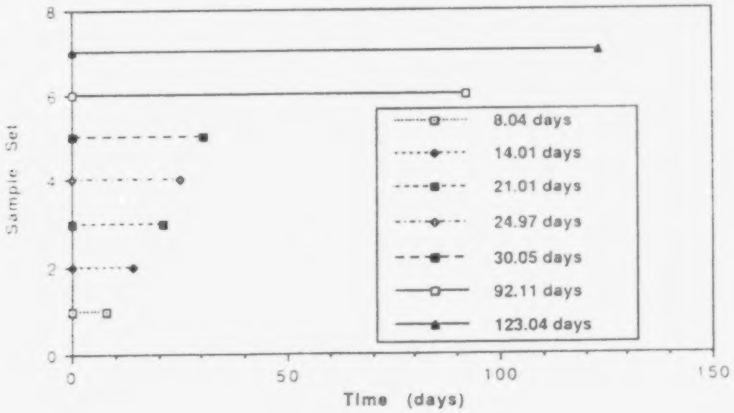


Figure 5.4.2.1
Experimental Schedule: Ductile Iron Coupons Exposed to the Untreated Water (Pumphouse No. 2)

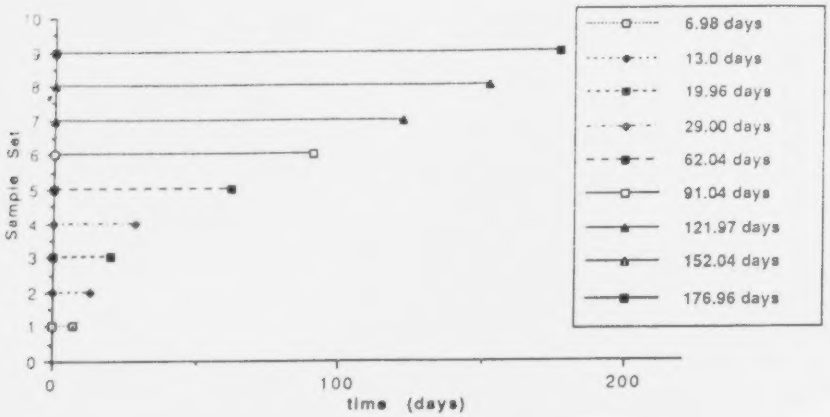
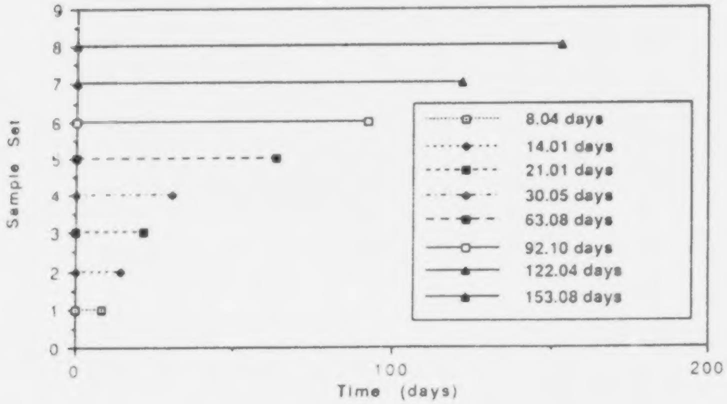


Figure 5.4.2.2
Experimental Schedule: Ductile Iron Coupons Exposed to the Treated Water (Pumphouse No. 4)



5.5 Results: Phase 1, Yellowknife In-situ Corrosion Tests Statistical Analysis of the Corrosion Rate Data

Tables 5.5.1.1, 5.5.1.2, 5.5.2.1 and 5.5.2.2 provide a summary of the statistical analysis of the corrosion rate data for each metal type exposed to the raw and treated supply water. Included in each table is the average, standard deviation, range, and calculation of outliers using the Q-test for a 90% probability for each sample set.

5.6 Specific Weight Loss

Figures 5.6.1 and 5.6.2 show the specific weight losses for ductile iron and copper for exposure to Yellowknife's raw and treated supply water. Shown for ductile iron, is the weight losses increasing linearly with contact time. The specific weight losses of ductile iron for exposure to the raw and treated supply water (pH range 6.5 to 7.5) after 4 weeks, were approximately 59 and 75 g/m^2. Millette (1985) measured for cast iron, after 4 weeks of immersion at pH 7, specific weight losses in the range of 60 and 65 g/m^2. The results for ductile iron for exposure to the raw water were very close to this range. The results, however, for ductile iron for exposure to the treated water exceeded this range. The relative linear rate at which the specific weight losses increased is indicative of uniform corrosion. Ductile iron coupons after exposure to the environment were examined for their total anode and cathode areas. Visual inspection of the coupons showed the anode and cathode areas of ductile iron coupons, for different exposure times, to be relatively equal to indicate uniform corrosion.

Shown in Figure 5.6.2 is the weight losses for copper increasing linearly with contact time. Millette (1985) reported the weight losses for

Table 5.5.1.1

Statistical Analysis of the Corrosion Rate Data for Exposure of Copper to the Untreated Water

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.98	0.1500	0.00207	0.1519-0.1478	N/A
3	11.00	0.0772	0.00042	0.0775-0.0769	1 Outlier
3	31.89	0.0641	0.00525	0.0694-0.0589	N/A
3	67.14	0.0748	0.00138	0.0758-0.0732	N/A
3	91.01	0.0679	0.00213	0.0689-0.0650	N/A
4	122.17	0.0544	0.00154	0.0531-0.0561	N/A

Table 5.5.1.2

Statistical Analysis of the Corrosion Rate Data for Exposure of Copper to the Treated Water

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	8.04	0.3927	0.02602	0.4282-0.3670	N/A
3	14.01	0.2275	0.00623	0.2333-0.2209	N/A
3	21.01	0.2028	0.01315	0.2152-0.1890	N/A
3	24.97	0.2078	0.01100	0.2003-0.2204	N/A
3	30.05	0.1970	0.00227	0.1989-0.1945	N/A
4	92.10	0.1932	0.01670	0.2124-0.1820	N/A
3	123.04	0.1829	0.00106	0.1839-0.1818	N/A

Table 5.5.2.1
Statistical Analysis of the Corrosion Rate Data for Exposure of Ductile Iron to the Untreated Water

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	6.98	2.475	0.09151	2.558-2.377	N/A
3	13.00	2.061	0.10148	2.156-1.954	N/A
3	19.96	1.863	0.29833	2.199-1.630	N/A
3	29.00	2.047	0.11246	2.175-1.964	N/A
3	62.04	1.710	0.00436	1.713-1.705	N/A
4	91.04	2.035	0.13422	2.117-1.843	N/A
3	121.97	1.761	0.03365	1.787-1.723	N/A
3	152.04	1.684	0.05032	1.716-1.626	N/A
3	176.96	1.671	0.10680	1.743-1.548	N/A

Table 5.5.2.2
Statistical Analysis of the Corrosion Rate Data for Exposure of Ductile Iron to the Treated Water

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	8.04	4.253	0.1288	4.394-4.142	N/A
3	14.01	3.141	0.1519	2.980-3.160	N/A
3	21.01	2.518	0.0652	2.571-2.445	N/A
3	30.05	2.655	0.2820	2.963-2.409	N/A
3	63.08	2.468	0.0217	2.430-2.497	N/A
4	92.10	2.535	0.01204	2.526-2.543	1 Outlier
3	122.04	2.469	0.2551	2.285-2.760	N/A
3	153.08	2.537	0.2675	2.279-2.813	N/A

copper after 4 weeks, for immersion in pH's from 6 to 8, to range from 4 to 14 g/m^2, to increase with decreasing pH. Weight losses for copper for exposure to the untreated water were much lower than that reported by Millette (1985). The weight losses for the untreated water gradually increased uniformly and after 90 days of exposure remained relatively constant. For exposure to the treated water the weight loss was 6 g/m^2 after 4 weeks which is slightly lower than what Millette reported for immersion in pH 7 water. The weight losses for the treated water continued to increase uniformly for the duration of the experiment.

The total weight changes of ductile iron in comparison to copper were, on average, 25 times greater for the raw water and 10 times greater for the treated water, after 4 weeks of exposure.

5.7 Corrosion Rates: In-situ Study, Phase 1

Figures 5.7.1 and 5.7.2 show the average corrosion rates of ductile iron and copper versus time for exposure to the untreated and treated water. In each figure the corrosion rates are shown decreasing with time. This observation is attributed to the protective properties corrosion scales have in reducing corrosion. The formation of scales on the surfaces of metals serves to protect the metal by inhibiting the transport of such species as dissolved oxygen which influence corrosion. The level of inhibition, however is dependent on the type of scale formed which is a function of the metal type, water composition at the metal's surface, and the water's bacteriological characteristics.

Figure 5.6.1
Specific Weight Losses of Ductile Iron for Exposure
to the City of Yellowknife's Untreated and Treated Supply Water

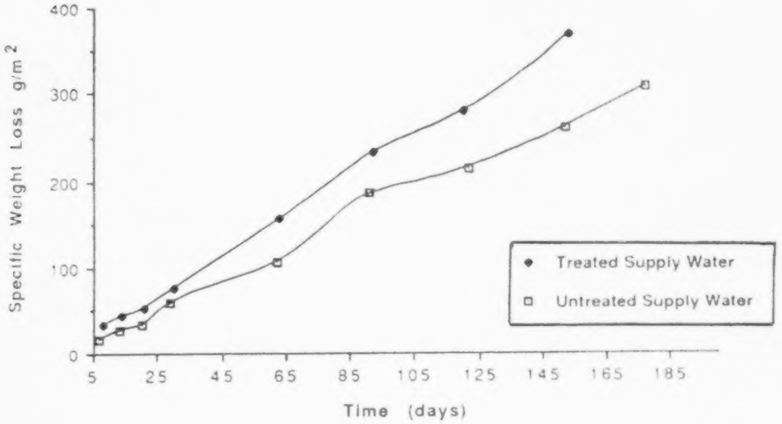
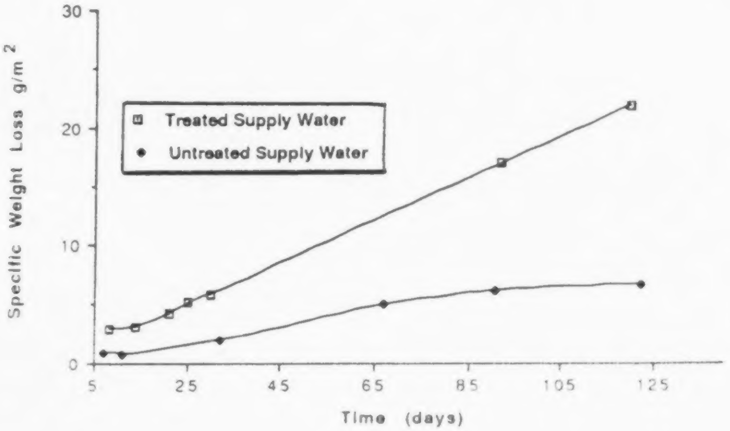


Figure 5.6.2
Specific Weight Losses of Copper for Exposure
to the City of Yellowknife's Untreated and Treated Supply Water



In Figures 5.7.1 and 5.7.2 the average corrosion rates of ductile iron and copper are, in each case, higher for test specimens exposed to the treated water versus exposure to the untreated water. Table 5.7.1 summarizes the long term (>60d) average corrosion rates for ductile iron and copper. The average corrosion rate (>60d) for ductile iron exposed to the treated water was 40% higher than the average rate for the raw water. For copper, similar results were observed, except the increase was by 65%.

Chemical treatment of Yellowknife's river water from the addition hydrofluosilicic acid, chlorine as free chlorine and, during the winter, heat, substantially increases the water's corrosivity. Fluoride, added as hydrofluosilicic acid, is known to intensify the corrosivity (Kennedy Engineers, 1978) of soft, low alkalinity waters by reducing both pH and alkalinity (AWWA, 1985). The effect Yellowknife's fluoridation program has on corrosion can be reduced by the use of alternative chemicals than hydrofluosilicic acid. Examples of alternative chemicals are: sodium fluoride, sodium silicofluoride, or ammonium silicofluoride.

The City presently chlorinates to obtain a total residual concentration of 1.0 mg/L and this residual is primarily free chlorine. Chlorine can accelerate corrosion by directly increasing the redox potential of the electrolyte to favour metal dissolution, or by undergoing a series of chemical reactions to produce hypochlorous acid, hypochlorite ion and chloride (AWWA, 1985). The strong oxidizing agents, hypochlorous acid and hypochlorite ion, can replace oxygen as a cathodic depolarizer in the mechanism of corrosion. For example, Larson (1975) showed residual chlorine concentrations in excess of 0.5 mg/L accelerated the corrosion of both ferrous and copper piping. The effect Yellowknife's chlorination

Figure 5.7.1
Corrosion Rates Versus Time for Copper Exposed to the City of Yellowknife's Untreated and Treated Supply Water

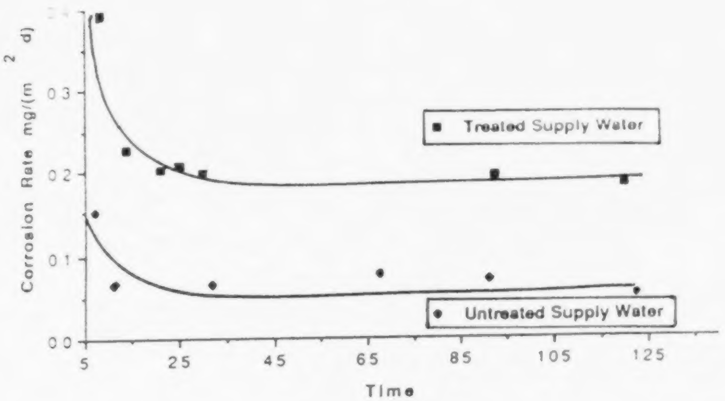


Figure 5.7.2
Corrosion Rates Versus Time for Ductile Iron Exposed to the City of Yellowknife's Untreated and Treated Supply Water

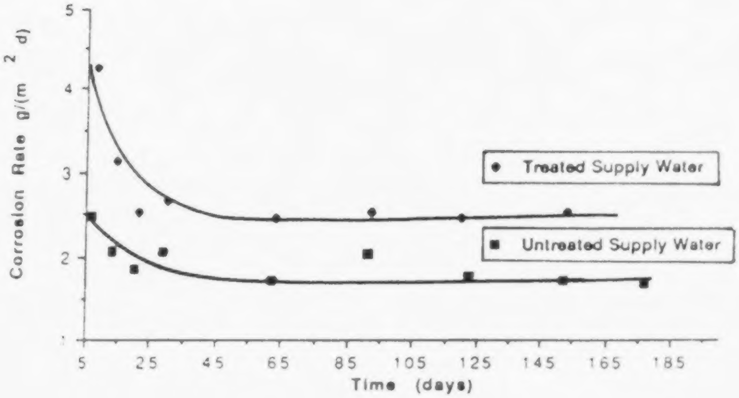


Table 5.7.1
Long Term Average Corrosion Rates (>60d)
Yellowknife In-situ Study, Phase 1

Metal Type	Average Corrosion Rate g/(m^2 d)	
	Treated Water	Raw Water
Copper	0.194	0.069
Ductile Iron	2.63	1.88

program has on the corrosion of its distribution system can be lessened by the addition of ammonia. Ammonia reacts with chlorine to form chloramines. Chloramines do not increase corrosion to nearly the same extent as does free chlorine (Larson, 1955). However, chlorine's influence, similar to that of oxygen, is lessened with the passivation of the metal's surface from the deposition of corrosion products.

Comparing the two metals, ductile iron corrodes at a rate of 13 times that of copper for the City's treated water, and 30 times that of copper for the raw water. This suggests the City's corrosion problem is attributable mostly to the corrosion of its ductile iron piping. Copper corrosion, however, cannot be neglected. Failure of copper tubing is relatively rare, rather the problem is the concern that resulting copper concentrations may exceed the limits stipulated in the drinking water standards. Studies (Shull and Becker, 1960) have shown that soft potable waters can develop high concentrations of copper in a very short period of time when the water in the system is stagnant and that flushing before use is required.

5.8 Resistivity Properties and Life Expectancy

Converting the corrosion rates from Table 5.7.1 from units of $g/(m^2 d)$ to units of mmpy, allows for both materials to be ranked according to the Ten-point Scale to determine their resistance properties and calculation of the time before 50% of the pipe wall is lost. Shown in Table 5.8.1 are the long term average corrosion rates (>60 d) expressed as mmpy.

According to the Ten-point Scale (see Appendix H), the resistance properties of each metal for exposure to the raw and treated supply water are as follows:

a. copper exposed to the raw water is highly resistant, given a point of one on the scale.

b. copper exposed to the treated water is highly resistant, given a point of two on the scale.

c. ductile iron exposed to the raw water is resistant, given a point of 4 on the scale.

d. ductile iron exposed to the treated water is fairly resistant, given a point of 5 on the scale.

For uniform corrosion, the service life of the material can be accurately predicted. Using the long term average corrosion rates, as determined, the estimated time periods before 50% of the pipe wall is lost for both metals exposed to each water type are as follows;

a. for a 150 mm diameter ductile iron pipe with a wall thickness of 6.4 mm exposed to (simulates worst case):
    i) the treated water the estimated time is approximately 24 years.
    ii) the raw water the estimated time is approximately 33 years.

b. for type K, copper pipe with a wall thickness of 1.6 mm exposed to;
    i) the treated water the estimated time is approximately 101 years.
    ii) the raw water the estimated time is approximately 286 years.

Table 5.8.1
Long Term Average Corrosion Rates (>60d)
Yellowknife In-situ Study, Phase 1

Metal Type	Average Corrosion Rate (mmpy)	
	Treated Water	Raw Water
Copper	0.0079	0.0028
Ductile Iron	0.135	0.096

Density for copper 8920 kg/m^3
density for ductile iron 7111 kg/m^3
ref: Metals Handbook, 1961

The above time estimates are valid only for conditions of uniform corrosion. The ductile iron corrosion rates are for the cement-lining removed. As well, the time estimates for ductile iron do not account for the mechanical strength provided by the graphite corrosion products that remain in place after the iron, associated with it, has been removed from glavanic corrosion. For example, LaQue (1964) found that under some circumstances, cast iron that has been completely graphitized can still perform the functions of the original cast iron.

According to AWWA (1985), corrosion rates of less than 0.13 mmpy are considered low and are a general indication of satisfactory service life of the metals tested and exposed in the piping system. For copper piping, the corrosion rate for the treated water expressed as mmpy was 0.0079 mmpy. This value is well below the 0.13 mmpy limit, to suggest the service life of copper is not seriously affected. For ductile iron piping, the corrosion rate for the treated water expressed as mmpy was 0.135 mmpy. This value slightly exceeds the 0.13 mmpy limit, to suggest its service life is moderately reduced. That is, the life expectancy of ductile iron exposed to the treated water is less than its desired design life expectancy of 75 years or longer for use in a distribution system.

The corrosion rates, as determined, are for a worse case scenario. The ductile iron corrosion rates simulate the condition in which the protective inside cement-lining has been removed due to either erosion and/or by dissolution, exposing the metal entirely to the environment.

6.0 Phase 2: Laboratory Immersion Study

6.1 Objective

The objective was to evaluate various inhibitory chemicals which could be added to reduce both ductile iron and copper corrosion.

6.2 Chemicals Tested

The inhibitory chemicals tested, either singly and/or in combination were: lime, carbon dioxide, sodium hydroxide, sodium carbonate, sodium silicate, and sodium hexametaphosphate. Table 6.2.1 lists the combination of inhibitory chemicals and the alternate control parameter settings at which they were evaluated.

6.3 Experimental Set-up

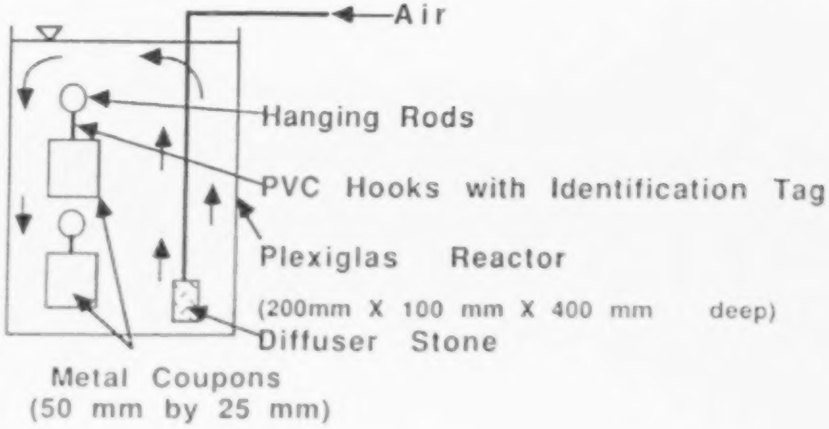
Testing of the inhibitory chemicals was conducted at the Environmental Engineering Laboratory, University of Alberta, Edmonton. The experimental set-up was identical for each chemical tested. However, the method of evaluation varied for each chemical depending on the selected control parameters.

The experimental apparatus consisted of Plexiglas batch reactors, with a fluid capacity of 8 L. Figure 6.3.1 illustrates a typical batch reactor. For mixing, the experimental water was aerated. The advantages of aeration were:

Table 6.2.1
Combination of Inhibitory Chemicals and the Alternate Control Settings at Which They Were Evaluated

Inhibitory Chemical(s)	**Control Parameter Settings**	**Treatment**
Sodium Carbonate	pH's: 7.5, 8.0 & 8.5	pH adjustment
Sodium Hydroxide	pH's: 7.5, 8.0 & 8.5	pH adjustment
Lime, CO_2 & Sodium Hydroxide	pH and Total Hardness (mg/L as $CaCO_3$): 75 mg/L at pH's 7.5 & 8.5, 25 mg/L at pH's 7.5 & 8.5, 50 mg/L at pH 8.0.	Total hardness, alkalinity and pH adjustment.
Sodium Hexametaphosphate	Phosphate Concentrations: 1, 3 & 5 mg/L as P.	Phosphate adjustment
Sodium Silicate	Silicate Concentrations: Ductile Iron Experiments: 6.9, 10.0, 13.4 & 21.0 mg/L as SiO_2 Copper Experiments: 2.1, 4.0 & 5.9 mg/L as SiO_2	Silicate adjustment
Raw Water	No chemicals added	Control
Chlorine	chlorine residual; approximately 1.0 mg/L following a 30 minute contact time	Control

Figure 6.3.1
Cross Sectional View of a Typical Batch Reactor Used in the Laboratory Immersion Tests


Air
Hanging Rods
PVC Hooks with Identification Tag
Plexiglas Reactor
(200mm X 100 mm X 400 mm deep)
Diffuser Stone
Metal Coupons
(50 mm by 25 mm)

a. both dissolved oxygen and carbon dioxide concentrations were continually maintained just at saturation; and

b. aeration produced the desired mixing in the direction parallel to the surfaces of metal coupons.

The disadvantages were that the batch reactors simulated an open system and the continuous addition of carbon dioxide caused the water's total carbonic concentration and acidity to increase with time. This, in turn caused the pH of the experimental water to gradually decrease with time. pH, in most cases, was used as the control parameter in evaluating the inhibitory chemicals. Its gradual decrease necessitated the addition of a pH adjustment chemical to readjust and to maintain the water's pH at the desired setting. Consequently, the periodic addition of a pH adjustment chemical to the experimental water produced varying changes in the water quality for a weekly liquid retention time.

To closely approximate the winter water temperature conditions in Yellowknife, the immersion tests were performed in the cold storeroom at a temperature of 5 to 7 °C. All components of the apparatus were made of non-metallic material. Test coupons were hung from 12.8 mm diameter Plexiglas rods using 6.4 mm diameter PVC hanging hooks. Pictured in Figures 6.3.2 and 6.3.3 are colour photographs of the experimental apparatus.

The location for hanging the coupons was opposite to the side on

Figure 6.3.2
Experimental Apparatus
Laboratory Immersion Tests

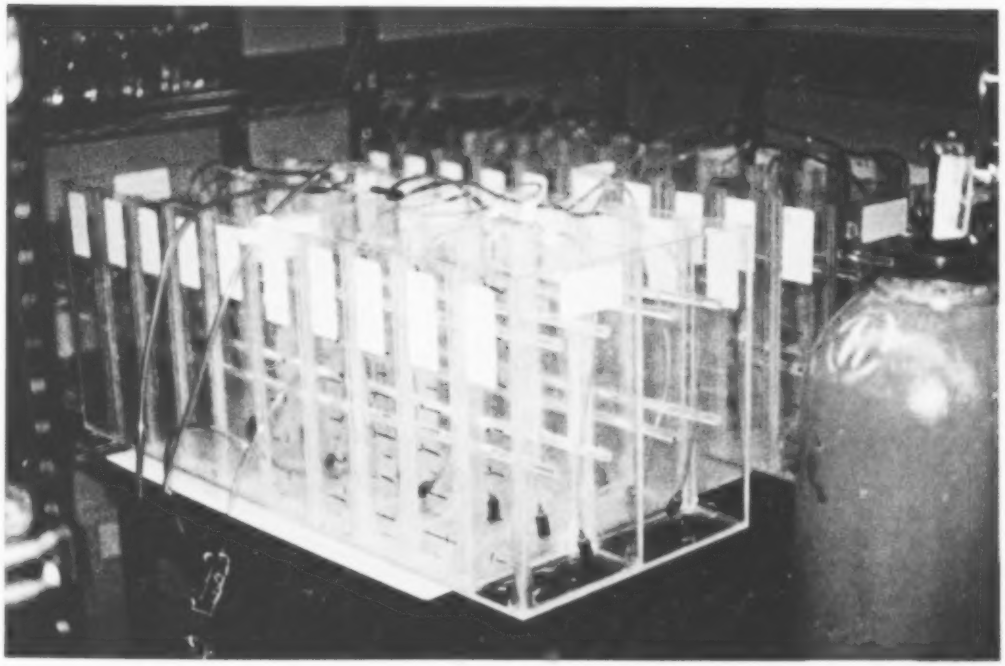
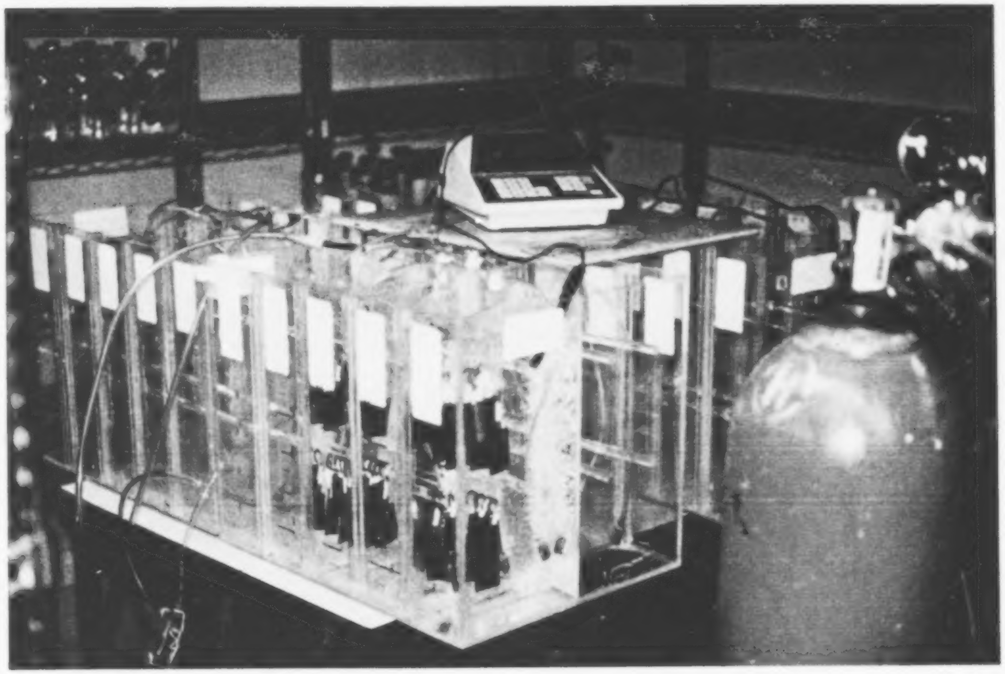


Figure 6.3.3
Experimental Apparatus
Laboratory Immersion Tests



which the diffuser stone for aerating the water was situated. This was to avoid the erosion effect rising air bubbles would have on the protective properties of the corrosion scales formed on the surfaces of coupons.

6.4 Methodology

The methodology used in evaluating each inhibitory chemical is detailed separately in the presentation of the results. Although, common to each test, was the experimental water used was from the Yellowknife River. Robinson Trucking Ltd. collected, using a 45 gal plastic container, from the Lake Pumping Station (Pumphouse No. 1), Yellowknife's untreated water and truck delivered this water to the university on a weekly basis. The experimental water was changed and chlorinated weekly, and the inhibitory chemical monitored and adjusted daily - if required. Test specimens were removed and inserted only when changing the experimental water.

6.4.1 Controls

Controls were established to serve a base comparison for assessment of the inhibitory performance of the chemicals evaluated. The controls consisted of no chemical addition to simulate the raw water, and the addition of only chlorine to simulate the treated water. Chlorine addition was to simulate the chlorination program currently practiced by the City. Approximately 1.0 mg/L, following a 30 minute contact time, of total residual chlorine was added. Hydrofluosilicic acid, however, was not added. Shown later, is the addition of hydrofluosilicic acid would of had little effect on influencing corrosion due to observed increases in alkalinities for the liquid's weekly retention time.

These tests were performed under the same conditions by which the inhibitory chemicals were evaluated. The experimental set-up was identical, and the experimental water was changed weekly. For the control with chlorine, the water was also chlorinated weekly. As well, test samples were inserted and removed only when changing the water.

6.5 Experimental Schedule

6.5.1 Copper Experiments

Figures 6.5.1.1 and 6.5.1.2 are the experimental schedules for the removal of copper coupons exposed to waters with and without chlorine. Sample sets consisted of three to four coupons each and were removed weekly. The durations of the tests were approximately 30 days for the water without chlorine, and 36 days for the water with chlorine.

6.5.2 Ductile Iron Experiments

Figures 6.5.2.1 and 6.5.2.2 are the experimental schedules for the removal of ductile iron coupons exposed to waters with and without chlorine. Sample sets consisted of two to three coupons each and were removed weekly. The duration for each of the tests was approximately 44 days.

6.6 Laboratory Water Characteristics for the Controls

Throughout the experiments, several water quality parameters were monitored on a weekly basis. These parameters were measured prior to

Figure 6.5.1.1
Experimental Schedule: Copper Control - No chlorine

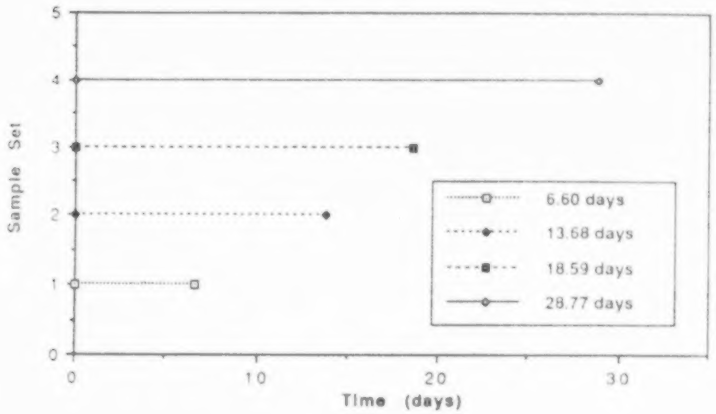


Figure 6.5.1.2
Experimental Schedule: Copper Control - With Chlorine

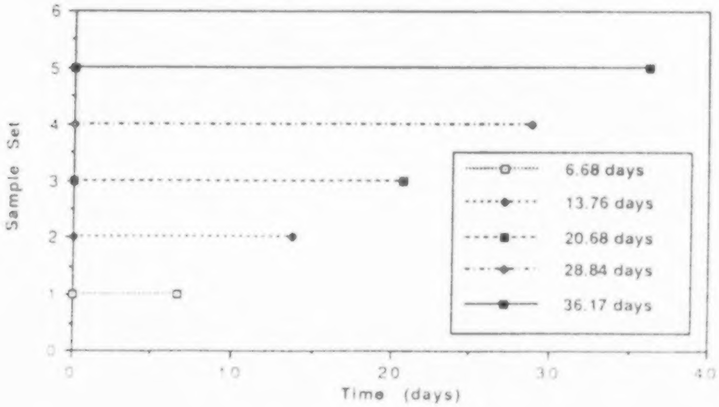


Figure 6.5.2.1
Experimental Schedule: Ductile iron Control - No chlorine

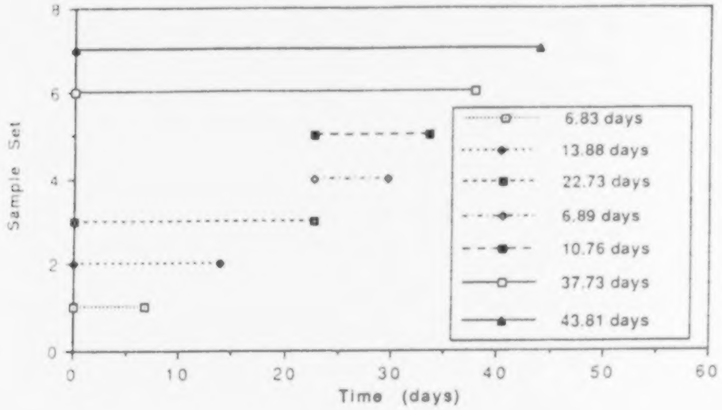
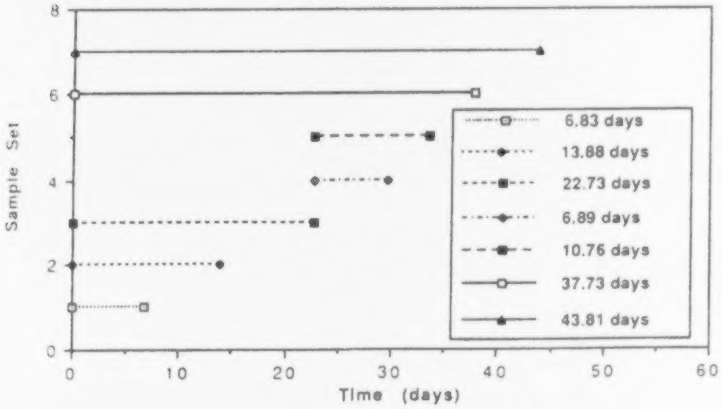


Figure 6.5.2.2
Experimental Schedule: Ductile Iron Control - With Chlorine



the immersion of coupons and again when changing the water on a weekly basis. Presented are the weekly variations in water quality for the immersion of ductile iron and copper coupons in waters, with and without chlorine.

6.6.1 Alkalinity

6.6.1.1 Copper Controls

Figure 6.6.1.1.1 shows the weekly changes in alkalinity of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the alkalinity changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 3.4 mg/L with a range of 3.2 to 3.7 mg/L as $CaCO_3$; and

b. Control - with chlorine: average increase was 5.3 mg/L with a range of 4.2 to 6.4 mg/L as $CaCO_3$.

6.6.1.2 Ductile Iron Controls

Figure 6.6.1.2.1 shows the weekly changes in alkalinity for the immersion of ductile iron in waters, with and without chlorine. The average increase and range by which the alkalinity changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 20.5 mg/L with a range of 14.6 to 28.4 mg/L as $CaCO_3$; and

Figure 6.6.1.1.1
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

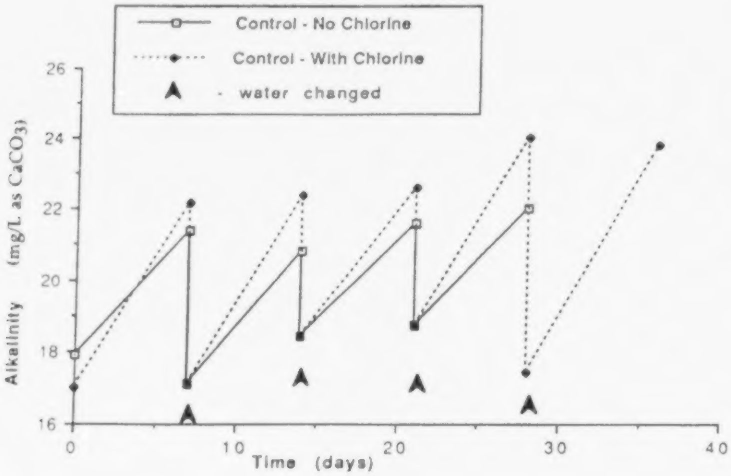
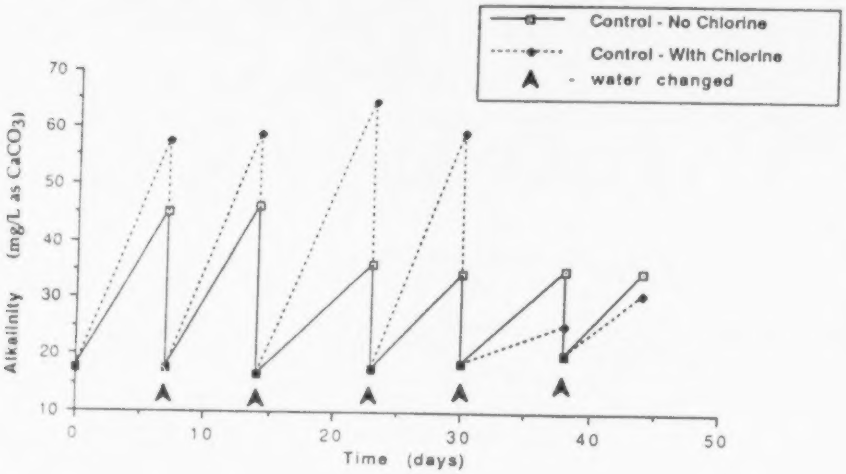


Figure 6.6.1.2.1
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



b. Control - with chlorine: average increase was 31.3 mg/L with a range of 5.2 to 47.9 mg/L as $CaCO_3$.

6.6.2 Calcium Concentration

6.6.2.1 Copper Controls

Figure 6.6.2.1.1 shows the weekly changes in the calcium concentration of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the calcium concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine added: average increase was 0.8 mg/L with a range of 0.6 to 1.0 mg/L as Ca^{2+}; and

b. Control - with chlorine added: average increase was 0.7 mg/L with a range of 0.4 to 1.0 mg/L as Ca^{2+}.

The calcium concentration of each control increased slightly during the liquid's weekly retention time. This is attributed to liquid losses due to evaporation.

6.6.2.2 Ductile Iron Controls

Figure 6.6.2.2.1 shows the weekly changes in calcium concentration of the experimental waters for the immersion of ductile iron, with and without chlorine. The average increase and range by which the calcium concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine : average increase was 1.2 mg/L with a range of 1.8 to 0.7 mg/L as Ca^{2+}; and

b. Control - with chlorine: average increase was 1.4 mg/L with a range of 3.6 to 0.7 mg/L as Ca^{2+}.

Similar to the copper experiments, the calcium concentrations of each control increased slightly for the liquid's weekly retention time. This is attributed to liquid losses due to evaporation.

6.6.3 Chloride Concentration

6.6.3.1 Copper Controls

Figure 6.6.3.1.1 shows the weekly changes in chloride concentration of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the chloride concentration changed for each control for a weekly liquid retention time was:

a. Control: with chlorine: average increase was 4.04 mg/L with a range of 0.70 to 8.46 mg/L as Cl^-; and

b. Control: without chlorine: average increase was 1.85 mg/L with a range of 1.53 to 2.36 mg/L as Cl^-.

Not known, however, is what the chloride concentration was for immediately after chlorinating the water. In chlorinating the water the chloride concentration was increased. The chloride concentration

Figure 6.6.2.1.1
Weekly Changes in Calcium Concentration of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

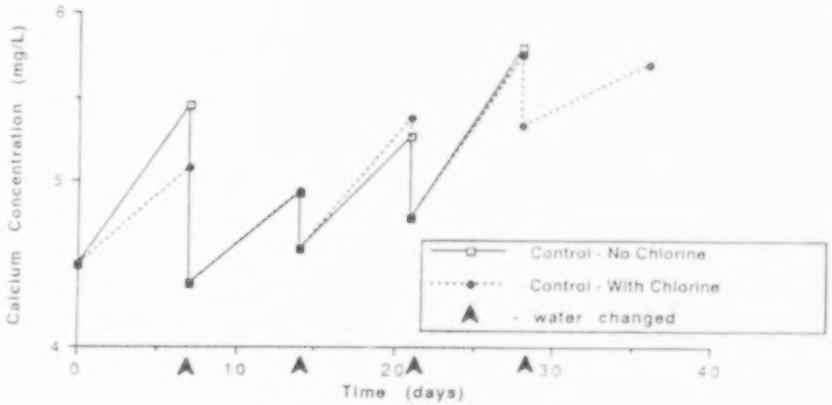
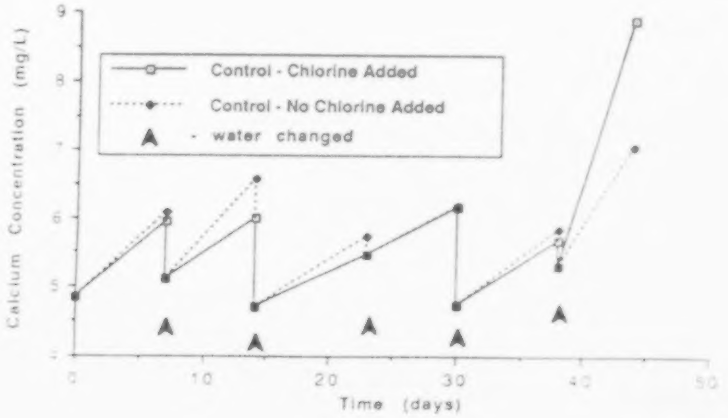


Figure 6.6.2.2.1
Weekly Changes in Calcium Concentration of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



increased for the control without chlorine, to possibly suggest surface contamination by adjacent reactors. However, the increases were less with respect to the control with chlorine. Chloride has less of an effect on influencing copper corrosion than for other metals.

6.6.3.2 Ductile Iron Controls

Figure 6.6.3.2.1 shows the weekly changes in chloride concentration of the experimental waters for the immersion of ductile iron, with and without chlorine. The average change and range by which the chloride concentration changed for each control for a weekly liquid retention time was:

a. Control: with chlorine: average increase was 3.34 mg/L with a range of 1.14 to 9.13 mg/L as Cl^-; and

b. Control: without chlorine: average decrease was 0.05 mg/L with a range of -0.37 to 0.17 mg/L as Cl^-.

The chloride concentration for the control with chlorine increased from chlorinating the water, whereas, for the control without chlorine, the chloride concentration decreased.

6.6.4 Copper Concentration

6.6.4.1 Copper Controls

Figure 6.6.4.1.1 shows the weekly changes in copper concentration of the experimental waters for the immersion of copper, with and without

Figure 6.6.3.1.1
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

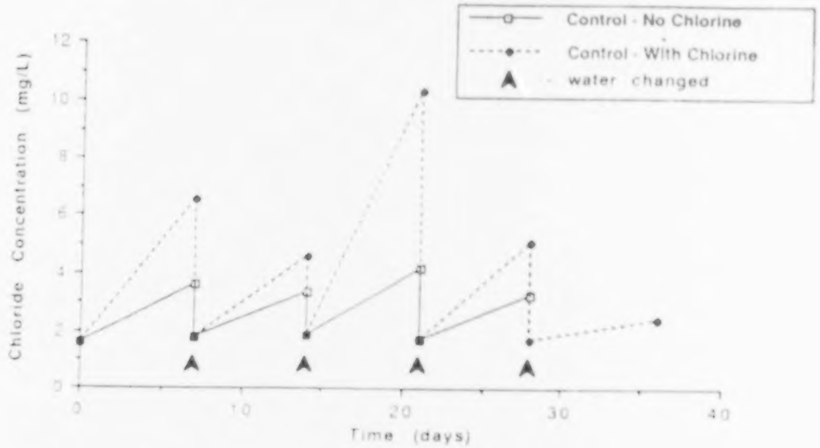
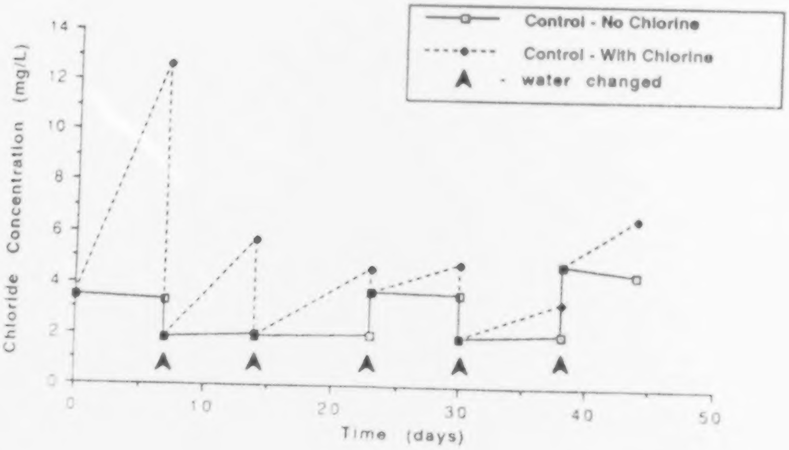


Figure 6.6.3.2.1
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



chlorine. The average increase and range by which the copper concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 1.16 mg/L with a range of 0.913 to 1.30 mg/L as Cu^{2+}; and

b. Control - with chlorine: average increase was 1.070 mg/L with a range of 0.76 to 1.30 mg/L as Cu^{2+}.

Both controls showed very similar increases in copper concentration throughout the tests, but this may be attributed to the difference in the number of coupons inserted for each control.

6.6.5 Dissolved Oxygen Concentration

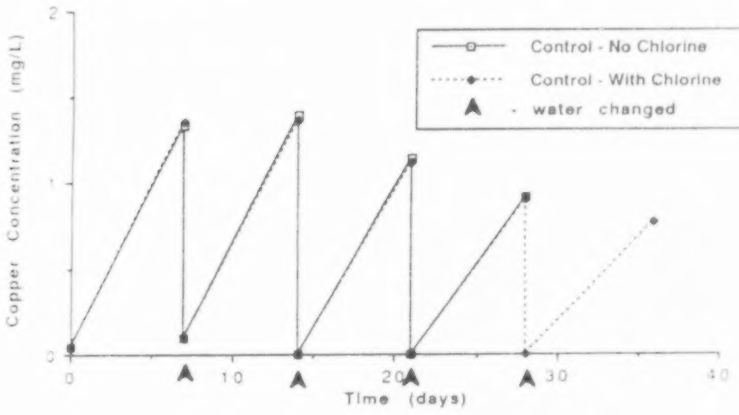
6.6.5.1 Copper Controls

Figure 6.6.5.1.1 shows the dissolved oxygen concentrations as measured when changing the experimental waters on a weekly basis for the immersion of copper, with and without chlorine. The dissolved oxygen concentrations of the experimental waters were kept relatively constant by the continual aeration of the waters. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. Control - no chlorine: average was 11.44 mg/L with a range of 11.40 to 11.48 mg/L as O_2; and

b. Control - with chlorine: average was 11.42 mg/L with a range of 11.40 to 11.45 mg/L as O_2.

Figure 6.6.4.1.1
Weekly Changes in Copper Concentration of the Experimental Waters for the Immersion of Copper, With and Without Chlorine



6.6.5.2 Ductile Iron Controls

Figure 6.6.5.2.1 shows the dissolved oxygen concentrations, as measured when changing the experimental waters on a weekly basis for the immersion of ductile iron, with and without chlorine. The dissolved oxygen concentrations of the experimental waters were kept relatively constant by continual aeration of the waters. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. Control - no chlorine: average was 11.26 mg/L with a range of 11.20 to 11.30 mg/L as O_2; and

b. Control - with chlorine: average was 11.27 mg/L with a range of 11.17 to 11.34 mg/L as O_2.

6.6.6 Electrical Conductivity

6.6.6.1 Copper Controls

Figure 6.6.6.1.1 shows the weekly changes in electrical conductivity of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the electrical conductivity changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 8.0 with a range of 1.0 to 12.0 umhos/cm; and

b. Control - with chlorine: average increase was 13.0 with a range of 11.0 to 17.0 umhos/cm.

Figure 6.6.5.1.1
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

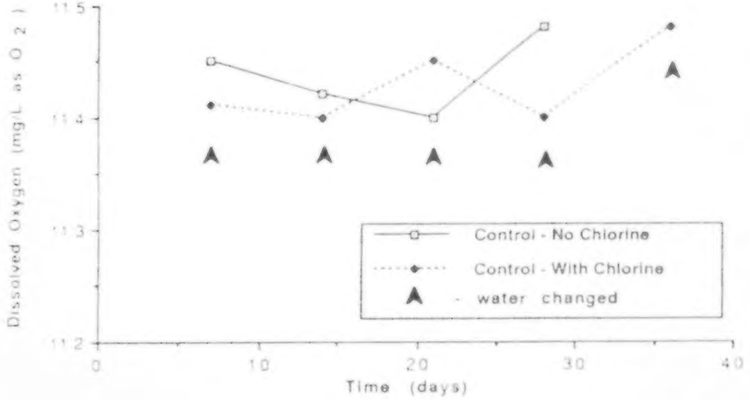
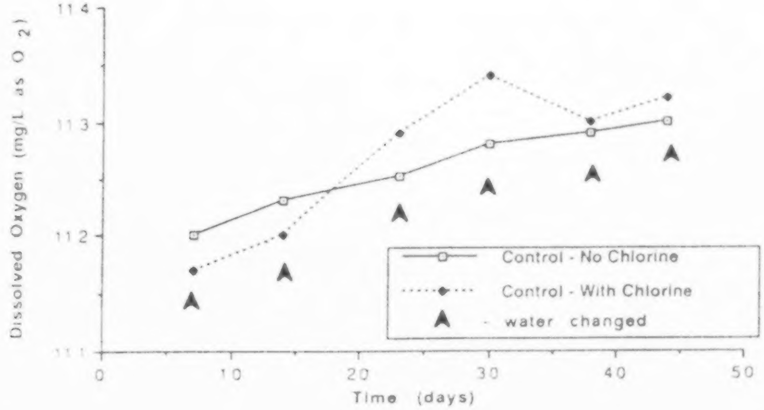


Figure 6.6.5.2.1
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



The increases in electrical conductivity of each control are the result of evaporation, corrosion and for the control with chlorine, chlorination. Higher were the increases for the control with chlorine and this is attributed to chlorination.

6.6.6.2 Ductile Iron Controls

Figure 6.6.6.2.1 shows the weekly changes in electrical conductivity for the immersion of ductile iron in waters with and without chlorine. The average increase and range by which the electrical conductivity changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 31.0 with a range of 15.0 to 48.0 umhos/cm; and

b. Control - with chlorine: average increase was 29.9 with a range of 7.0 to 79.0 umhos/cm.

The electrical conductivity increased for each control. The data does not display any trends for differentiating between the two controls. However, the increases are shown decreasing with time, and this is attributed to the removal of coupons.

6.6.7 Hardness Concentration

6.6.7.1 Copper Controls

Figure 6.6.7.1.1 shows the weekly changes in the total hardness concentration of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the

Figure 6.6.6.1.1
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

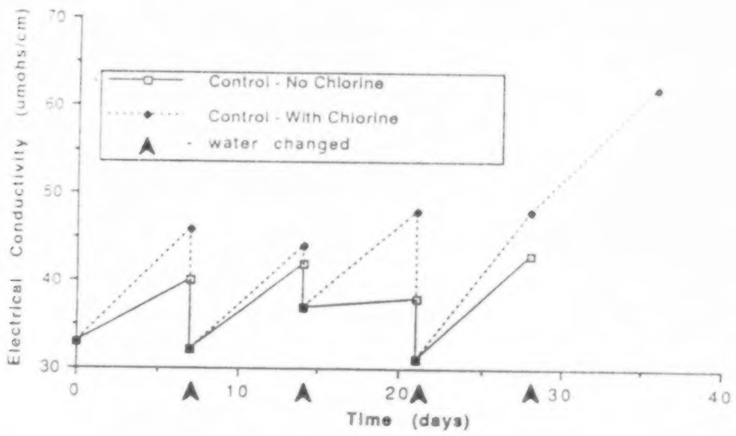
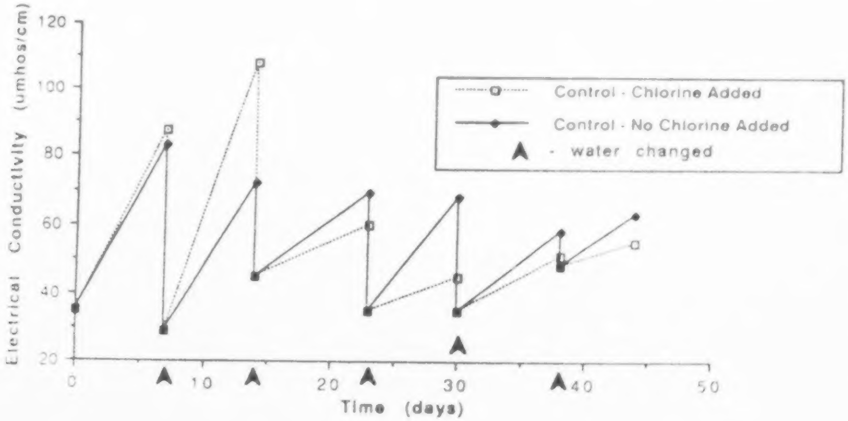


Figure 6.6.6.2.1
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



total hardness concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 0.3 mg/L with a range of -0.2 to 1.0 mg/L as $CaCO_3$; and

b. Control - with chlorine: average increase was 0.7 mg/L with a range of 0.0 to 1.4 mg/L as $CaCO_3$.

In general, the total hardness concentration of each control increased slightly from corrosion and from liquid losses due evaporation.

6.6.7.2 Ductile Iron Controls

Figure 6.6.7.2.1 shows the weekly changes in the total hardness concentration for the immersion of ductile iron in waters, with and without chlorine. The average increase and range by which the total hardness concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 4.4 mg/L with a range of 10.0 to 4.0 mg/L as $CaCO_3$; and

b. Control - with chlorine: average increase was 6.0 mg/L with a range of 10.2 to 3.4 mg/L as $CaCO_3$.

Similarly, the total hardness concentration of each control increased. The reasons are the same as for the copper results.

Figure 6.6.7.1.1
Weekly Changes in Total Hardness Concentration of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

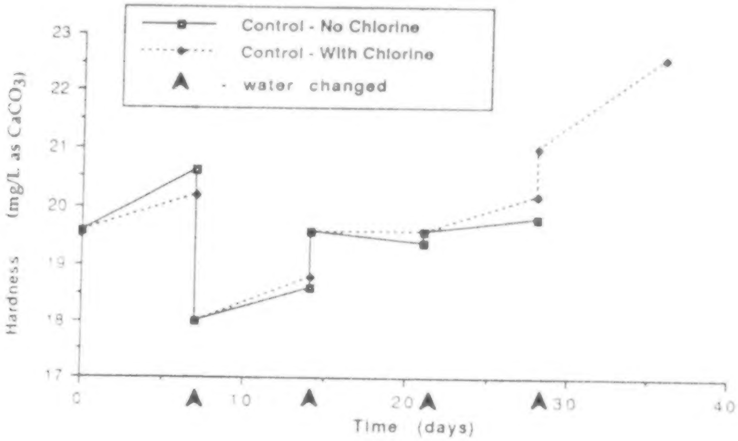
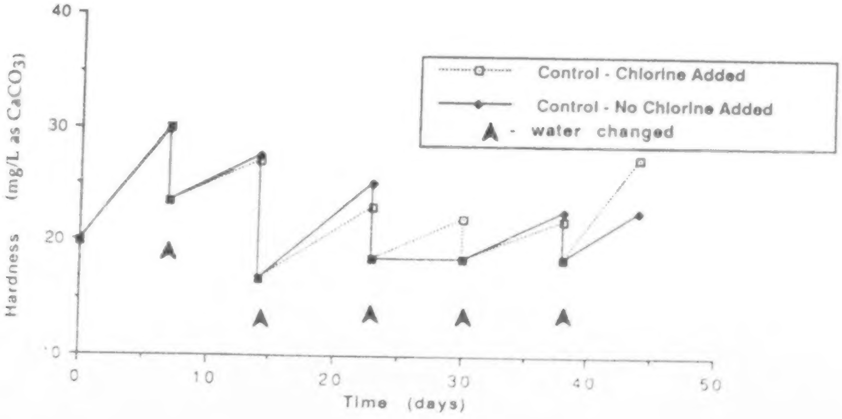


Figure 6.6.7.2.1
Weekly Changes in Total Hardness Concentration of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



6.6.8 Iron Concentration

6.6.8.1 Ductile Iron Controls

Figure 6.6.8.1.1 shows the weekly changes in iron concentration of the experimental waters for the immersion of ductile iron, with and without chlorine. The average increase and range by which the iron concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 2.95 mg/L with a range of 0.53 to 6.88 mg/L as total iron; and

b. Control - with chlorine: average increase was 4.385 mg/L with a range of 1.17 to 11.66 mg/L as total iron.

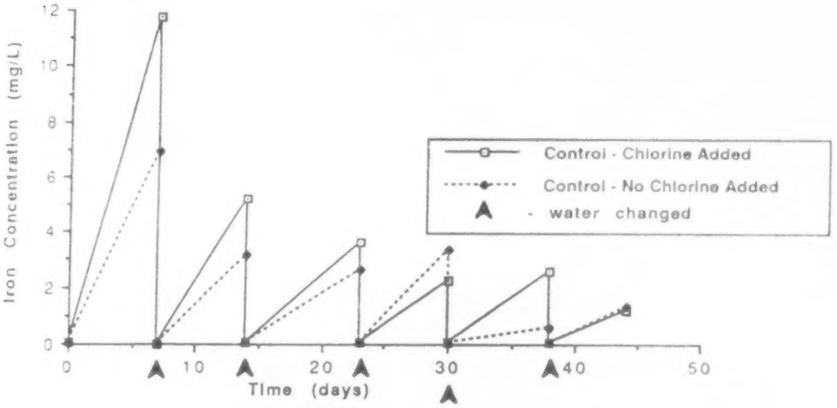
Increases in the iron concentration were, in most cases, higher for the control with chlorine. This observation is supportive of the higher initial corrosion rates associated with the control with chlorine. As well, the increases were initially high and later decreasing with time. The decrease in iron concentration with time is associated with a reduction in corrosion and the removal of iron coupons.

6.6.9 Magnesium Concentration

6.6.9.1 Copper Controls

Figure 6.6.9.1.1 shows the weekly changes in magnesium concentration of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the

Figure 6.6.8.1.1
Weekly Changes in Iron Concentration of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



magnesium concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 0.17 mg/L with a range of 0.15 to 0.19 mg/L as Mg^{2+}; and

b. Control - with chlorine added: average increase was 0.18 mg/L with a range of 0.10 to 0.26 mg/L as Mg^{2+}.

The magnesium concentration of each control increased slightly for a weekly liquid retention time. The magnitude of the increases were similar for each control. Increases are from liquid losses due to evaporation.

6.6.9.2 Ductile Iron Controls

Figure 6.6.9.2.1 shows the weekly changes in magnesium concentration of the experimental waters for the immersion of ductile iron, with and without chlorine. The average decrease and range by which the magnesium concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average decrease was 0.03 mg/L with a range of -0.24 to 0.216 mg/L as Mg^{2+}; and

b. Control - with chlorine: average decrease was 0.042 mg/L with a range of -0.27 to 0.25 mg/L as Mg^{2+}.

Unlike the copper results, the magnesium concentration of each control decreased for a weekly liquid retention time. This observation can be the result of magnesium locally precipitating at the metal's surface to become intermixed with the corrosion scale.

Figure 6.6.9.1.1
Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

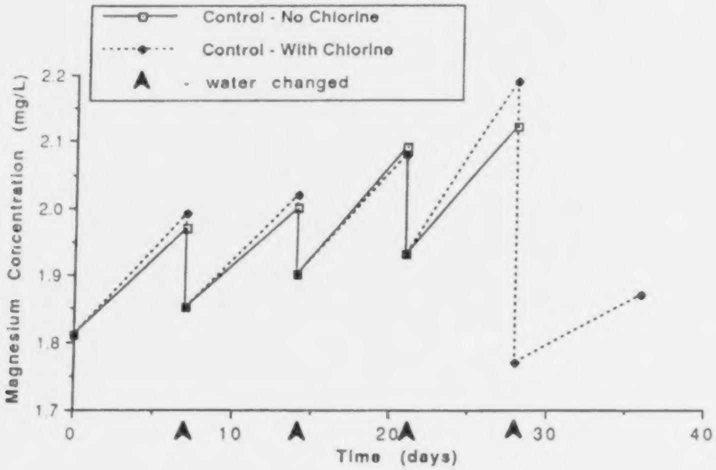
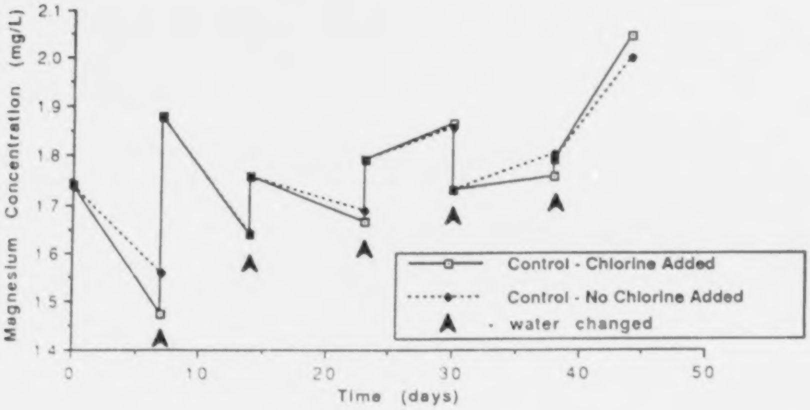


Figure 6.6.9.2.1
• Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



6.6.10 pH

6.6.10.1 Copper Controls

Figures 6.6.10.1.1 and 6.6.10.1.2 show the daily changes in pH of the experimental waters for the immersion of copper, with and without chlorine.

6.6.10.2 Ductile Iron Controls

Figure 6.6.10.2.1 shows the daily changes in pH for the immersion of ductile iron in waters, with and without chlorine.

6.6.11 Silicate Concentration

6.6.11.1 Copper Controls

Figure 6.6.11.1.1 shows the weekly changes in silicate concentration of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the silicate concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 0.03 mg/L with a range of -0.04 to 0.14 mg/L as Si; and

b. Control - with chlorine: average increase was 0.12 mg/L with a range of 0.06 to 0.25 mg/L as Si.

The silicate concentration of each control, increased slightly from liquid losses due to evaporation.

Figure 6.6.10.1.1
Daily Changes in pH of the Experimental Water for the Immersion of Copper, With Chlorine

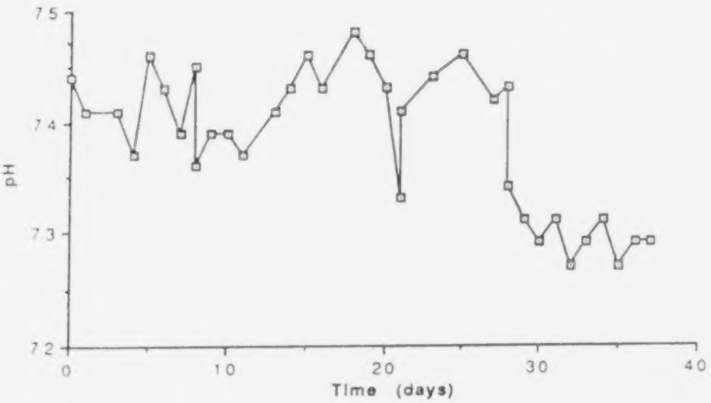


Figure 6.6.10.1.2
Daily Changes in pH of the Experimental Water for the Immersion of Copper, Without Chlorine

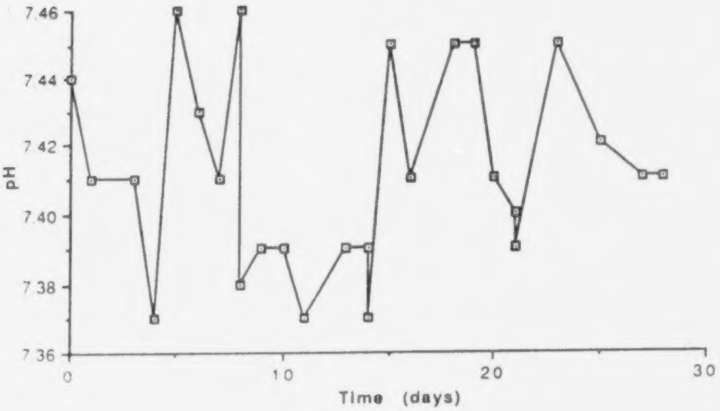
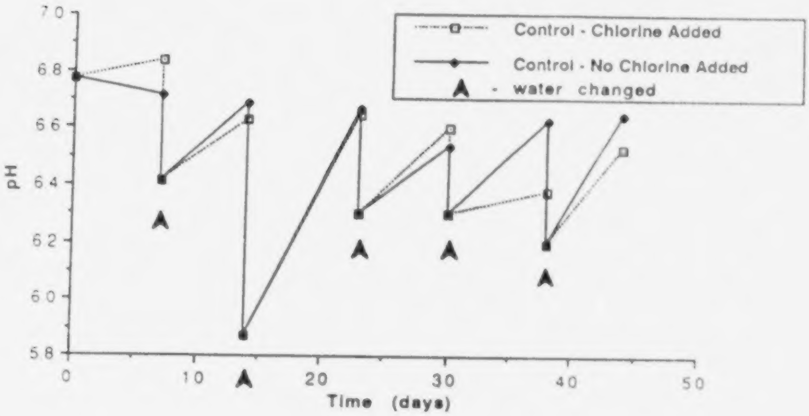


Figure 6.6.10.2.1
Daily Changes in pH of the Experimental Water for the Immersion of Ductile iron, With and Without Chlorine



6.6.11.2 Ductile Iron Controls

Figure 6.6.11.2.1 shows the weekly changes in silicate concentration of the experimental waters for the immersion of ductile iron, with and without chlorine. The average increase and range by which the silicate concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 0.62 mg/L
with a range of 0.08 to 1.04 mg/L as Si; and

b. Control - with chlorine: average increase was 0.587 mg/L
with a range of 0.01 to 1.32 mg/L as Si.

Similar to the copper results, the silicate concentration of each control increased. However, the magnitudes of the increases were greater. Silicon is an ingredient of ductile iron, therefore increases are attributed mainly to ductile iron corrosion.

6.6.12 Sodium Concentration

6.6.12.1 Copper Controls

Figure 6.6.12.1.1 shows the weekly changes in sodium concentration of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the sodium concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 0.46 mg/L
with a range of 0.37 to 0.52 mg/L as Na^+; and

Figure 6.6.11.1.1
Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

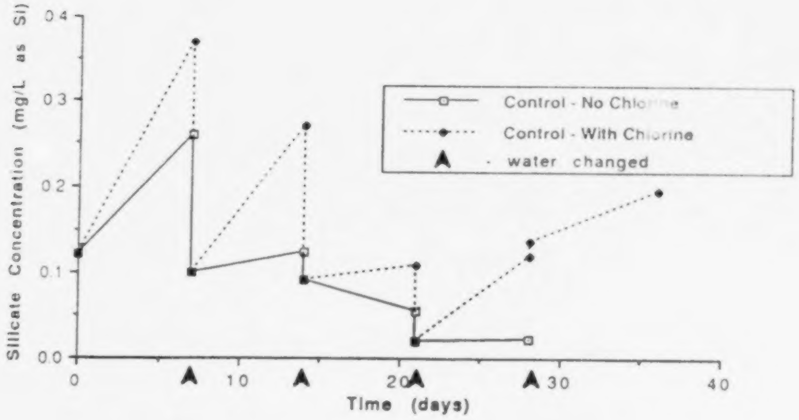
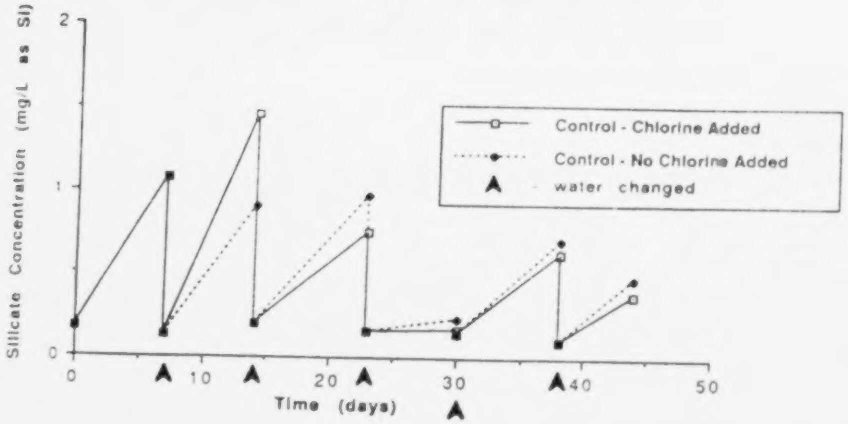


Figure 6.6.11.2.1
Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



b. Control - with chlorine: average increase was 2.92 mg/L with a range of 2.26 to 4.52 mg/L as Na^+.

The sodium concentration for the control without chlorine increased slightly from liquid losses due to evaporation. However, for the control with chlorine, the increases in sodium concentration were higher. This is due mainly to chlorination and to a lesser extent from evaporation.

6.6.12.2 Ductile Iron Controls

Figure 6.6.12.2.1 shows the weekly changes in sodium concentration for the immersion of ductile iron in waters, with and without chlorine. The average increase and range by which the sodium concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 8.09 mg/L with a range of 4.76 to 15.32 mg/L as Na^+; and

b. Control - with chlorine: average increase was 8.13 mg/L with a range of 1.04 to 21.87 mg/L as Na^+.

The increases in sodium concentration of each control were similar, with the control without chlorine showing slightly higher increases after the second week. This may be attributed to possible sodium contamination from adjacent reactors used for evaluating pH adjustment chemicals. The increases, however, were small enough not to have affected the test.

Figure 6.6.12.1.1
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

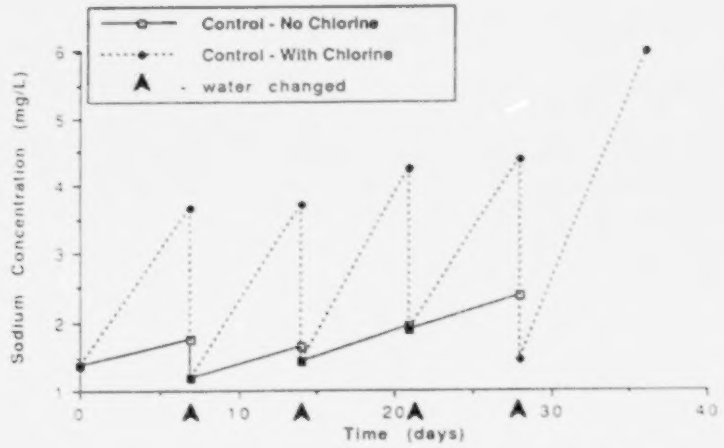
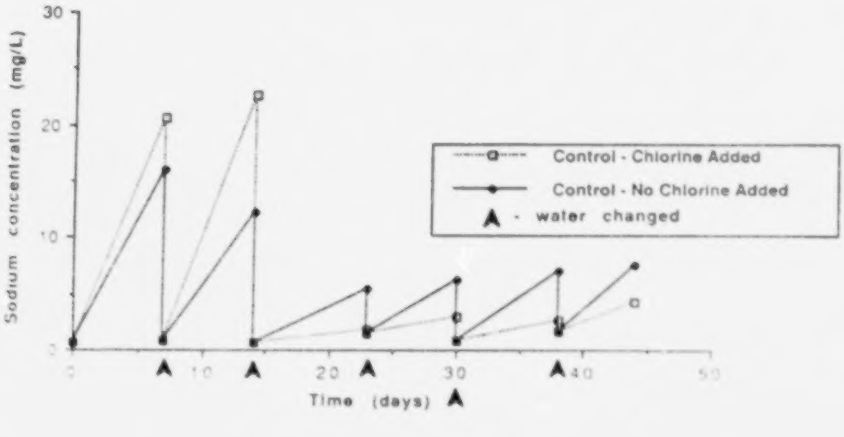


Figure 6.6.12.2.1
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



6.6.13 Sulfate Concentration

6.6.13.1 Copper Controls

Figure 6.6.13.1.1 shows the weekly changes in sulfate concentration of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the sulfate concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 0.02 mg/L with a range of -0.40 to 0.48 mg/L as SO_4^{2-}; and

b. Control - with chlorine: average increase was 0.46 mg/L with a range of -0.04 to 1.08 mg/L as SO_4^{2-}.

6.6.13.2 Ductile Iron Controls

Figure 6.613.2.1 shows the weekly changes in sulfate concentration of the experimental waters for the immersion of ductile iron, with and without chlorine. The average decrease and range by which the sulfate concentration changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average change was -1.61 mg/L with a range of -2.95 to -0.71 mg/L as SO_4^{2-}; and

b. Control - with chlorine: average change was -2.10 mg/L with a range of -0.87 to 3.75 mg/L as SO_4^{2-}.

Figure 6.6.13.1.1
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Copper, With and Without Chlorine

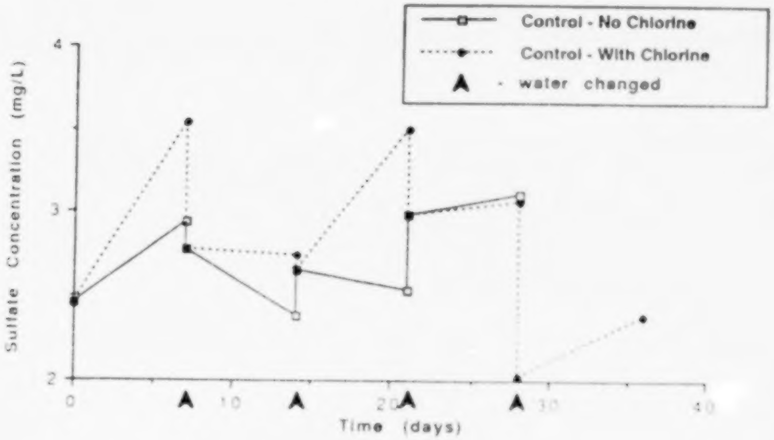
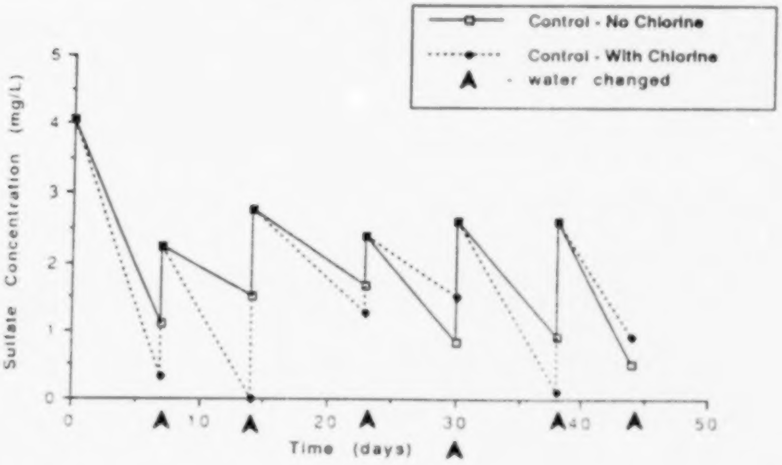


Figure 6.6.13.2.1
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Ductile Iron, With and Without Chlorine



6.6.14 Temperature

The temperature at which the experiments were performed ranged from 5 to 7 °C.

6.6.15 Turbidity

6.6.15.1 Copper Controls

Figure 6.6.15.1.1 shows the weekly changes in turbidity of the experimental waters for the immersion of copper, with and without chlorine. The average increase and range by which the turbidity changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 0.8 with a range of 0.4 to 1.1 NTU; and

b. Control - with chlorine: average increase was 0.6 with a range of 0.3 to 0.8 NTU.

The turbidity of each control increased slightly from corrosion, and from liquid losses due to evaporation.

6.6.15.2 Ductile Iron Controls

Figure 6.6.15.2.1 shows the weekly changes in turbidity of the experimental waters for the immersion of ductile iron, with and without chlorine. The average increase and range by which the turbidity changed for each control for a weekly liquid retention time was:

a. Control - no chlorine: average increase was 12.5 with a range of 9.0 to 16.6 NTU; and

b. Control - with chlorine: average increase was 21.4 with a range of 5.2 to 58.6 NTU.

The turbidity of each control increased greatly from corrosion. Shown in Figure 6.6.15.2.1, are the increases in turbidity, initially high and later decreasing with time. Decreasing turbidity is attributed to lower corrosion rates and the removal of coupons. As well, after the second week of exposure, the increases in turbidity were similar between controls. This is attributed to there being little difference in the corrosion rate of each control.

Figure 6.6.15.1.1
Weekly Changes in Turbidity of the
Experimental Waters for the Immersion of Copper,
With and Without Chlorine

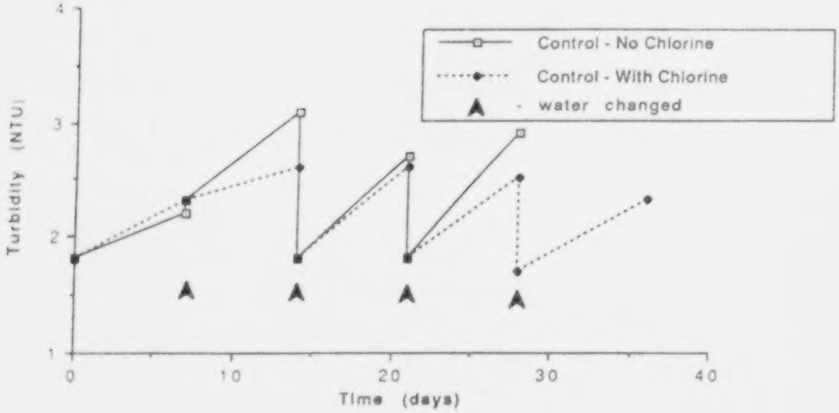
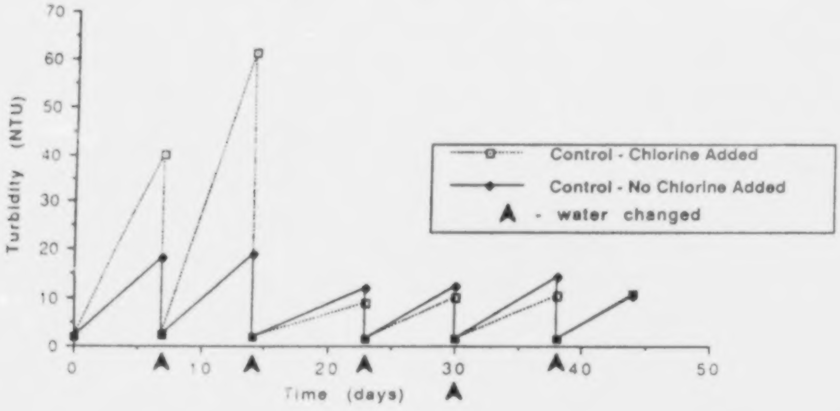


Figure 6.6.15.2.1
Weekly Changes in Turbidity of the
Experimental Waters for the Immersion of Ductile Iron,
With and Without Chlorine



6.7 Specific Weight Loss

6.7.1 Copper Controls

Figure 6.7.1.1 shows the weight losses versus time for copper, with and without chlorine. For the control without chlorine, the weight losses were initially low and later began increasing uniformly for the remaining duration of the experiment. For the control with chlorine, the weight losses were initially high, but after two weeks began increasing uniformly at a lower rate compared to the control without chlorine.

6.7.2 Ductile Iron Controls

Figure 6.7.2.1 shows the weight losses versus time for ductile iron, with and without chlorine. For the control with chlorine, the weight losses were initially higher than that of the control without chlorine. However, after two weeks the weight losses were similar for each control.

6.8 Statistical Analysis of the Corrosion Rate Data for the Controls With and Without Chlorine

Tables 6.8.1.1, 6.8.1.2, 6.8.2.1, and 6.8.2.2 provide a summary of the statistical analysis of the corrosion rate data for each control. Included in each table is the average, standard deviation, range, and calculation of outliers using the Q-test for a 90% probability for each sample set. In addition, the means of each sample set for each exposure time were compared using the paired t-test at a 95% probability.

Figure 6.7.1
Specific Weight Losses of Copper With and Without Chlorine

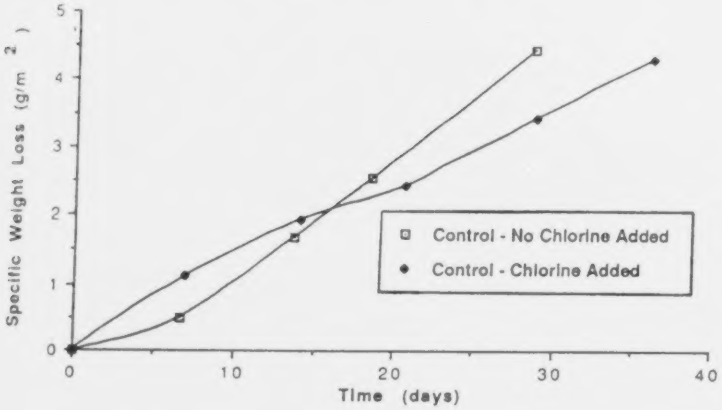
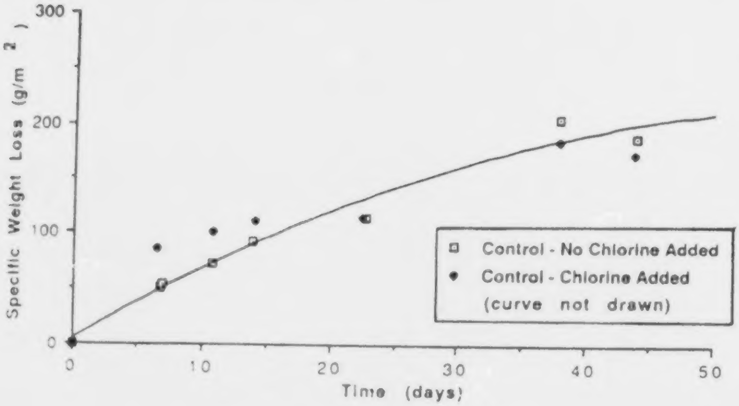


Figure 6.7.2
Specific Weight Losses of Ductile iron With and Without Chlorine



6.8.1 Copper Results

The difference between the corrosion rates of the copper controls, with and without chlorine, were initially significantly different at a 95% confidence level. The two controls were significantly different for the sample dates, 7 and 21 days. Chlorination of the experimental water produced a residual that was primarily free chlorine, and the retention time of this residual was tested to be less than a day. Aeration and exposure to light are responsible for the loss of residual. Consequently, there was little difference between the water quality of each control after the second day of the experminetal water's weekly retention time. To determine what effect this was to have in simulating Yellowknife's treated water, the City's chlorination program and history was review. The City has, in the past, experienced difficultly in maintaining an adequate chlorine residual in all parts of its water distribution system. In-situ tests of Yellowknife's distribution water showed the chlorine residual to be low or nonexistent at the outer parts of the network (Smith, 1989). Based on this it may be reasonable to assume the control simulating the treated water was representative of actual conditions and depicted the treated water quality in Yellowknife.

6.8.2 Ductile Iron Results

Comparison of the ductile iron controls, with and without chlorine, were initially significantly different at a 95% confidence level. The two controls were significantly different for the initial two weeks of exposure, showing the dramatic effect chlorine has on the corrosion of clean metal coupons. However, after an exposure time of 14 days, the rates of corrosion

Table 6.8.1.1
Statistical Analysis of the Copper Corrosion Rate Data for the Control Without Chlorine

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.60	0.0734	0.0052	0.0783 - 0.0680	N/A
3	13.68	0.1220	0.0074	0.1304 - 0.1165	N/A
2	20.59	0.1356	0.0004	0.1356 - 0.1360	N/A
3	28.77	0.1534	0.0129	0.1647 - 0.1394	N/A

Table 6.8.1.2
Statistical Analysis of the Copper Corrosion Rate Data for the Control With Chlorine

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.68	0.1682	0.0021	0.1696 - 0.1667	1 outlier
3	13.76	0.1157	0.0071	0.1239 - 0.1107	N/A
2	20.68	0.1166	0.0048	0.1200 - 0.1132	N/A
4	28.84	0.1178	0.0129	0.1304 - 0.1006	N/A
4	36.17	0.1187	0.0037	0.1229 - 0.1139	N/A

Table 6.8.1.3
Comparison of Means of the Corrosion Rate Data For the Controls With and Without Chlorine by Comparing $t_{calculated}$ to $t_{tabulated}$ for a 95 % Probability.

Time (days)	Comparison of Controls With and Without Chlorine
7	23.623 > 2.776 Difference is Significant
14	1.064 < 2.776 Difference is Not Significant
21	5.591 > 4.303 Difference is Significant
29	1.812 < 2.574 Difference is Not Significant

Table 6.8.2.1
Statistical Analysis of the Ductile Iron Corrosion Rate Data for the Control Without Chlorine

No of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.83	7.41	0.346	7.80 - 7.15	N/A
3	13.88	6.65	0.279	6.97 - 6.46	N/A
3	22.73	5.01	0.204	5.24 - 4.85	N/A
2	6.89	7.88	0.262	8.06 - 7.69	N/A
2	10.76	6.70	0.028	6.72 - 6.68	N/A
2	37.73	5.44	0.010	5.44 - 5.43	N/A
2	43.81	4.28	0.163	4.39 - 4.16	N/A

Table 6.8.2.2
Statistical Analysis of the Ductile Iron Corrosion Rate Data for the Control With Chlorine

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.47	13.27	0.205	13.41 - 13.12	1 outlier
3	13.97	7.90	0.050	7.94 - 7.87	1 outlier
2	22.42	5.10	0.078	5.15 - 5.04	N/A
2	37.73	4.89	0.042	4.92 - 4.86	N/A
2	43.73	3.95	0.022	3.96 - 3.93	N/A
2	6.98	13.02	0.283	13.22 - 12.82	N/A
2	10.76	9.31	0.120	9.43 - 9.18	N/A

Table 6.8.2.3
Comparison of Means of the Corrosion Rate Data For the Controls With and Without Chlorine by Comparing $t_{calculated}$ to $t_{tabulated}$ for a 95 % Probability.

Time (days)	Comparison of Controls With and Without Chlorine
7	20.978 > 3.182 Difference is Significant
14	5.979 > 3.182 Difference is Significant
23	0.584 < 2.776 Difference is Not Significant
38	18.015 > 4.303 Difference is Significant
44	2.845 < 4.303 Difference is Not Significant
7	18.848 > 4.303 Difference is Significant
11	30.000 > 4.303 Difference is Significant

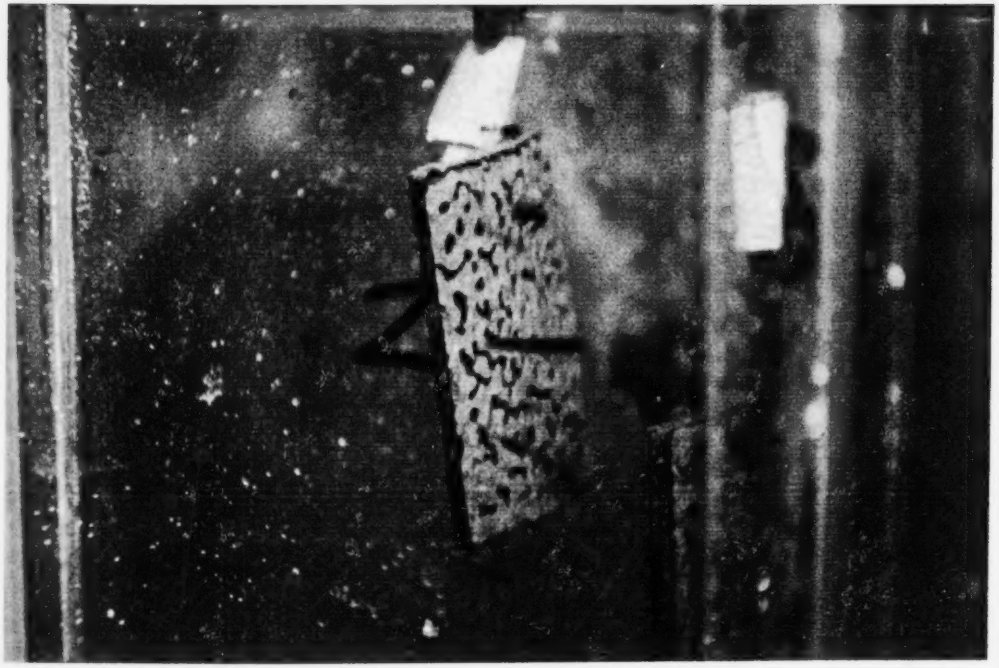
of the two controls were essentially the same. Ductile iron becomes less reactive with its environment with time due to the deposition of corrosion products on its surface (Figure 6.8.2.1). Consequently, after two weeks, the ductile iron coupons exposed to the treated water had formed a sufficient protective layer of corrosion products that the periodic presence of chlorine no longer significantly influenced corrosion.

6.9 Corrosion Rates

6.9.1 Copper Controls

To compare the dramtic effect chlorine, as free chlorine, has on copper corrosion, refer to Figure 6.9.1.1. Figure 6.9.1.1 shows the addition of chlorine as only having initially increased copper corrosion. Chlorine is not shown to exhibit the same influence on corrosion as was observed in the in-situ study of Phase 1. This is attributed to several reasons. Firstly, only chlorine was added to the experimental water to simulate Yellowknife's treated water. Hydrofluosilicic acid was not added. It was felt that the increases in alkalinity observed for the liquid's weekly retention time would have greatly reduced the influence on corrosion of adding hydrofluosilicic acid. Secondly, and more important, the loss of chlorine residual from the experimental water through aeration and exposure to light greatly reduced the time the residual was present in solution for influencing corrosion. Analysis of the experimental water for chlorine residual, after one day, was very low to non-existent to indicate there was little difference in water quality between each control for the liquid's weekly retention time. Lastly, metal coupons exposed to the environment for a sufficient period of time had developed a layer of corrosion scales to

Figure 6.8.2.1
Scale Formation on Ductile Iron Coupons for the
Control Without Chlorine
(Taken After Two Weeks of Exposure)



act as a barrier, further reducing chlorine's influence. Unlike the ductile iron controls, the copper corrosion rates of the control without chlorine exceeded the corrosion rates of the control with chlorine for a two week exposure time. This phenomena is believed to be attributed to chlorine having accelerated the growth of an initial thick cuprous oxide film on the metal's surface to achieve earlier protection.

Studies by Trussell (1984) indicated the influence of chlorine on copper corrosion is dependent on temperature, concentration and on the species of chlorine. Experiments in Portland, Oregon showed that copper corrosion did not increase as a result of chloramines being present at normal concentrations (AWWA, 1985). However, chlorine present, either as hypochlorous acid or as a hypochlorite solution, as is the case for the City's treated water, has been shown to cause generalized corrosion and may be the initiator of type 1 rapid pitting (AWWA, 1985). The consensus, however, among practicing engineers is chlorine, present in concentrations of less than 1.0 mg/L, does not contribute significantly to the corrosion of copper (AWWA, 1985). Although chlorine, depending on the chlorination program practiced, the chlorine species present, the stability of the water and whether or not the water is stagnant, may greatly influence corrosion.

To graphically show the dramatic effect chlorine had on copper corrosion, refer to Figure 6.9.1.2. In Figure 6.9.1.2, the two controls are compared in the form of a bar graph for the initial two weeks of exposure. The bar graph also shows the percent differences in the corrosion rates of the raw water compared to the chlorinated water. To evaluate the inhibitory action of the different chemicals, their performance is compared

Figure 6.9.1.1
Comparison of the Copper Corrosion Rates Versus Time for the Controls With and Without Chlorine

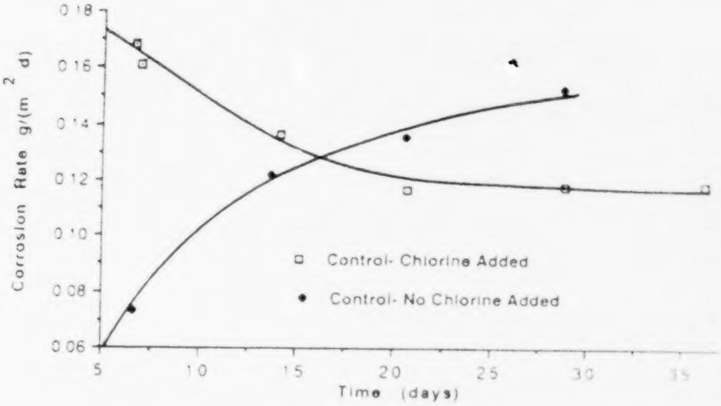
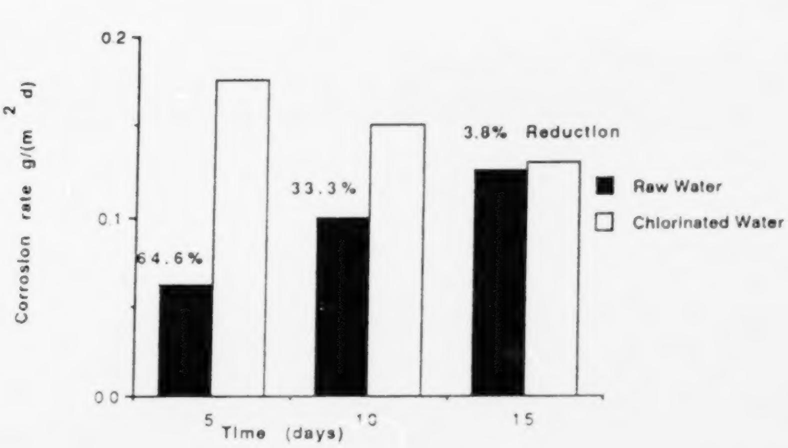


Figure 6.9.1.2
Bar Graph Comparison of the Copper Corrosion Rates of the Raw Water to that of the Chlorinated Water for the Initial Two Weeks of Exposure



to the control with chlorine. Unable to duplicate the phenomena observed in Phase 1, of the in-situ study, the comparison between the inhibitory chemicals and the control simulating the treated water is restricted to the initial two weeks of exposure where the difference in corrosion rates is most apparant.

Copper is observed to exhibit a higher standard deviation for samples belonging to the same set in comparison to ductile iron. This variation is attributable to the differences in the type of scale formation associated with each metal type. Copper exposed to potable water, will form a surface scale consisting of cuprous oxide and basic copper salts. The loss of cuprous ions from the surface of the metal as a result of corrosion, forms vacancies which increase to develop into cavities to reduce the area to which the cuprous oxide film is attached. As a result, the very thin cuprous oxide scale is easily spalled by the water's turbulent action. This phenomena was visually observed to vary among samples in the laboratory and may account for the differences in corrosion rates between samples belonging to the same set.

6.9.2 Ductile Iron Controls

To compare the dramtic effect chlorine, as free chlorine, has on ductile iron corrosion, refer to Figure 6.9.2.1. Figure 6.9.2.1 shows the addition of chlorine as only having initially increased ductile iron corrosion. Similar to the copper results, is that chlorine is not shown to exhibit the same influence on corrosion as was observed in the in-situ study of Phase 1. This is attributed to the same reasons given for the copper results.

To graphically show the dramatic effect chlorine had on intensifying the corrosion of clean ductile iron coupons, refer to Figure 6.9.2.2. In Figure 6.9.2.2, the two controls are compared in the form of a bar graph for the initial two weeks of exposure. The bar graph also shows the percent differences in the corrosion rates of the raw water compared to the chlorinated water. To evaluate the inhibitory action of the different chemicals, their performance is compared to the control with chlorine. Unable to duplicate the phenomena observed in Phase 1 of the in-situ study, the comparison between the inhibitory chemicals and the control simulating the treated water, is restricted to the initial two weeks of exposure where the difference in corrosion rates is most apparant.

6.10 Limitations to Laboratory Batch Tests

Limitations of the laboratory batch study were that the tests did not provide for accurate estimates of chemical dosages for use in the distribution system. Instead, the study was useful in showing the tendency of these chemicals for the range of dosages for which they are effective in reducing corrosion.

The laboratory study (phase 2) failed to duplicate the findings observed in Phase 1 of the in-situ study. This is attributed to several reasons. Firstly, not all the chemicals used in the treatment of Yellowknife's drinking water were used in the laboratory batch study. Of those chemicals used, only chlorine was added to the control to which the inhibitory chemicals were to be compared. Hydrofluosilicic acid, used to fluoridate the water, was not added. However, for the conditions under which the experiments were conducted, it is believed the addition of

Figure 6.9.2.1
Comparison of the Ductile Iron Corrosion Rates Versus Time for the Controls With and Without Chlorine

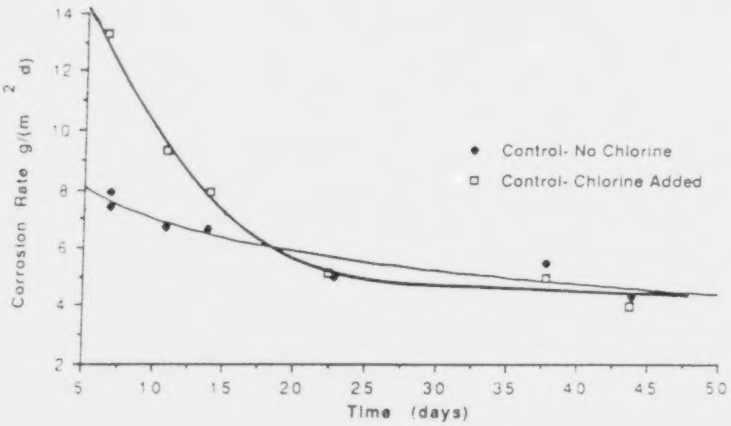
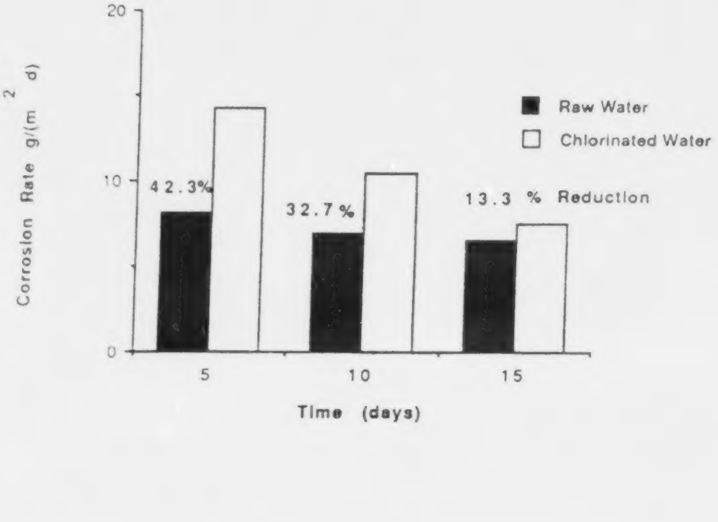


Figure 6.9.2.2
Bar Graph Comparison of the Ductile Iron Corrosion Rates of the Raw Water to that of the Chlorinated Water for the Initial Two Weeks of Exposure



hydrofluosilicic acid would have had little influence on corrosion. This is due to increases in alkalinity of the experimental waters for the liquid's weekly retention time. Secondly, and more important, was the loss of chlorine residual from aeration and exposure to light. This greatly reduced the time the residual was present in solution for influencing corrosion. Analysis for chlorine residual showed that after one day, the total residual concentration present was very low or non-existent. Consequently, the loss of chlorine residual, together with the diminishing effect chlorine has with the passivation of the metal's surface by the deposition of corrosion products, dramatically reduced chlorine's influence on corrosion. However, the absence of chlorine from the treated water does not necessarily mean it was not representative of Yellowknife's treated water. The City has, in the past, experienced difficultly in maintaining an adequate chlorine residual in all parts of its water distribution system. In-situ tests of Yellowknife's distribution water showed the chlorine residual to be low or nonexistent at the outer parts of the network (Smith, 1989). Based on this it may be reasonable to assume the control simulating the treated water was representative of actual conditions and depicted the treated water quality in Yellowknife.

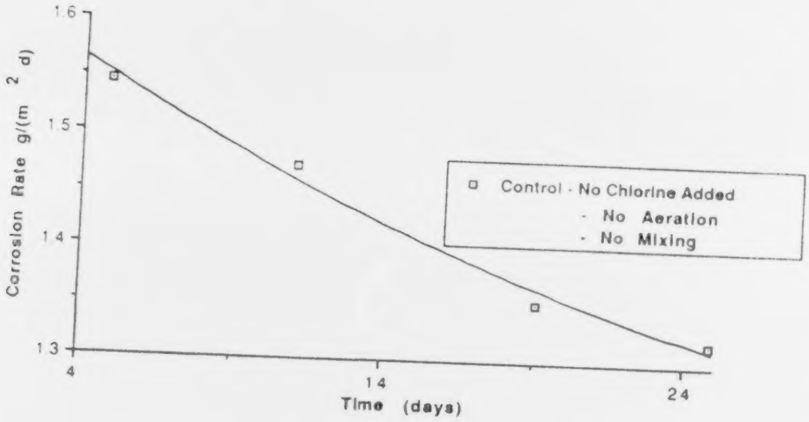
As well, the relative corrosion rates of the chemicals compared were generally the same after a 25 day exposure time. This observation is believed to be the influence of the environment rather than the inhibitory effect of the chemicals. Turbulent conditions and the water, saturated with respect to dissolved oxygen, are believed to be the factors responsible for controlling the corrosion rates. Mixing was such that the transfer of the inhibitory chemical to the metal surface was not impaired. However, the deposition of the insoluble salts and the rate of scale loss from the surface was likely controlled by the turbulent conditions. Consequently, this may have restricted the inhibitory action of the chemicals in further reducing the corrosion rates below those observed. As a result, comparison of the inhibitory chemicals is restricted to the initial two weeks of exposure for evaluation of their effectiveness, in which the difference in the performance of each chemical is most apparent.

6.11 Control - No Aeration, No Mixing, and No Chlorine

6.11.1 Ductile Iron Experiments

An experiment was conducted in which ductile iron coupons were exposed to Yellowknife's untreated water without the aid of aeration. The purpose of the test was to evaluate what influencing effect aeration had on corrosion. The results (Figure 6.11.1.1) were similar to the ductile iron results of the in-situ study, Phase 1. The corrosion rates, without aeration and mixing, were slightly lower than that of the Phase 1 ductile iron results. The results indicate aeration and mixing as having contributed greatly to increasing the corrosion rates in the laboratory batch tests.

Figure 6.11.1.1
Ductile Iron Corrosion Versus Time for the
Conditions: No Mixing, No Aeration, and No Chlorine



7.0 Results for the Inhibitor: Polyphosphate

7.1 Methodology

Polyphosphate in the form of sodium hexametaphosphate was evaluated for its ability to reduce ductile iron and copper corrosion. The concentrations investigated were 1, 3, and 5 mg/L as P. Concentrations were monitored daily and adjusted when required. For quality assurance, the experimental water was immediately sampled, after dosing with polyphosphate, to ensure the desired concentration had been achieved. In addition, the water was chlorinated weekly to obtain a total residual concentration of approximately 1.0 mg/L, following a 30 minute contact time. The experimental water was changed weekly, at which time chlorine and polyphosphate were added. The water was sampled daily and analyzed for total phosphate using the Vanadomolybdophosphoric Acid Colorimetric Method, Standard Methods (AWWA-AHPA-WPCF, 1989). When needed, additional polyphosphate was added to maintain the desired concentration levels.

7.2 Summary of Water Quality Changes

Tables 7.2.1 and 7.2.2 are a summary of the changes in water quality for the polyphosphate tests. The values listed are the average change and the range by which each paramenter changed for a weekly liquid retention time. For more detailed information refer to Appendix A.

Table 7.2.1
Water Quality Summary Sheet for the Copper Experiments of the Polyphosphate Tests

Parameter	Control Setting					
	1 mg/L as P		3 mg/L as P		5 mg/L as P	
	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	2.7	1.9 to 3.5	4.5	3.0 to 6.0	2.9	0.3 to 4.7
Calcium	0.55	0.15 to 0.62	0.57	0.18 to 0.69	0.62	0.46 to 0.73
Chloride	5.53	2.10 to 13.46	5.04	3.00 to 6.59	3.51	2.50 to 5.08
Copper	0.66	0.56 to 0.73	1.14	0.87 to 1.48	1.37	1.09 to 1.42
Dissolved Oxygen	11.54	11.48 to 11.61	11.54	11.48 to 11.58	11.54	11.50 to 11.58
Electrical conductivity (umhos/cm)	18.0	14.0 to 21.0	17.0	14.0 to 21.0	19.0	16.0 to 24.0
Magnesium	0.07	0.01 to 0.15	0.14	0.03 to 0.29	0.15	0.11 to 0.21
pH	7.46	7.40 to 7.58	7.48	7.43 to 7.58	7.46	7.41 to 7.54
Silicate	0.08	0.04 to 0.15	0.12	0.04 to 0.25	0.10	0.04 to 0.15
Sodium Hexametaphosphate	0.1	-0.2 to 0.1	0.2	-0.3 to 0.1	0.2	-0.1 to 0.2
Sodium	2.91	2.35 to 3.23	5.29	4.73 to 5.64	6.49	5.85 to 6.96
Sulfate	-2.85	-2.71 to -2.98	-2.85	-2.71 to -2.98	-2.85	-2.71 to -2.98
Total Hardness ($CaCO_3$)	-0.2	-0.4 to 0.2	0.0	-0.6 to 0.4	0.2	-1.4 to 1.4
Turbidity (NTU)	0.5	0.0 to 1.0	0.8	0.5 to 1.1	0.8	0.3 to 1.4

Unless otherwise stated all values are in mg/L

Table 7.2.2
Water Quality Summary Sheet for the Ductile Iron Experiments of the Polyphosphate Tests

Parameter	Control Setting					
	1 mg/L as P		3 mg/L as P		5 mg/L as P	
	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	4.5	3.9 to 5.1	5.9	4.3 to 7.0	10.7	6.0 to 13.7
Calcium	-0.25	-0.64 to 0.11	-0.68	-1.34 to -0.48	-1.09	-1.32 to -0.84
Chloride	3.00	2.03 to 4.64	3.48	2.90 to 4.06	7.06	2.32 to 15.37
Dissolved Oxygen	11.27	11.25 to 11.29	11.24	11.20 to 11.27	11.20	11.15 to 11.25
Electrical conductivity (umhos/cm)	15.0	10.0 to 17.0	16.0	11.0 to 22.0	24.0	20.0 to 27.0
Magnesium	-0.20	-0.26 to -0.07	-0.34	-0.47 to -0.07	-0.39	-0.54 to -0.17
Iron	12.21	6.07 to 22.61	13.88	9.91 to 18.12	21.80	12.95 to 33.32
pH	7.49	7.39 to 7.56	7.51	7.42 to 7.57	7.52	7.46 to 7.59
Silicate	0.66	0.35 to 0.99	0.68	0.40 to 0.92	0.91	0.37 to 1.31
Sodium	4.30	3.49 to 5.54	8.11	6.12 to 10.04	11.46	7.69 to 16.74
Sodium Hexametaphosphate	-0.3	-1.0 to 0.2	-0.7	-2.4 to 0.2	-1.3	-4.0 to -0.4
Sulfate	-1.66	-2.33 to -0.83	-1.02	-1.54 to -0.83	-1.58	-2.66 to -0.74
Total Hardness ($CaCO_3$)	-0.4	-3.0 to 1.4	-3.1	-2.0 to -4.0	-4.9	-3.1 to -8.0
Turbidity (NTU)	28.0	7.3 to 55.2	16.5	3.4 to 32.2	33.7	6.4 to 79.2

Unless otherwise stated all values are in mg/L

7.3 Specific Weight Loss

7.3.1 Copper Experiments

Figure 7.3.1.1 shows the specific weight losses of copper, with time and polyphosphate concentration. Increased polyphosphate concentration did not result in a marked change in the weight losses of copper.

7.3.2 Ductile Iron Experiments

Figure 7.3.2.1 shows the specific weight losses of ductile iron with time and polyphosphate concentration. Increased polyphosphate concentration, increased the weight losses of ductile iron. The weight changes were similar for the polyphosphate concentrations 1 mg/L and 3 mg/L as P, with the 3 mg/L as P concentration, showing slightly higher losses. However, weight changes were much higher for the 5 mg/L as P concentration in comparison to the lower concentrations.

In addition, the magnitude of the weight losses for ductile iron at each setting decreased as contact time increased. This is attributed to the passivation of the surfaces of metal coupons from the formation of corrosion scales reducing corrosion with time.

7.4 Statistical Analysis of the Corrosion Rate Data

Tables 7.4.1.1, 7.4.1.2, 7.4.1.3, 7.4.1.4, 7.4.2.1, 7.4.2.2, 7.4.2.3 and 7.4.2.4 provide a summary of the statistical analysis of the corrosion rate data for each polyphosphate concentration. Included in each table is the average, standard deviation, range, and calculation of outliers using the Q-test for a 90% probability for each sample set. In addition, the means of each sample

Figure 7.3.1.1
Specific Weight Losses Versus Time for Copper Immersed in Polyphosphate Treated Waters

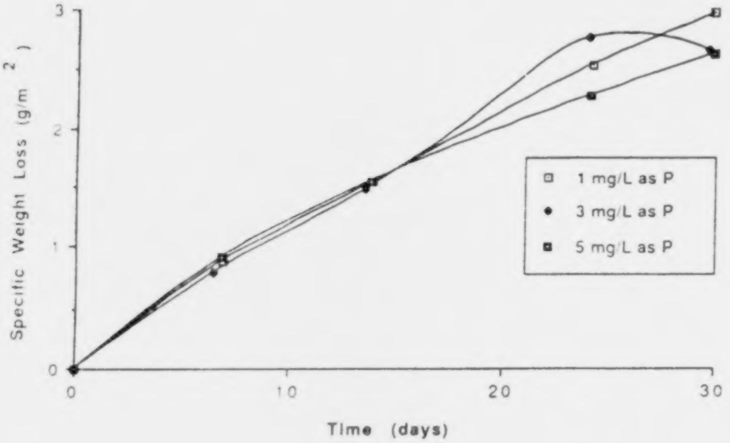
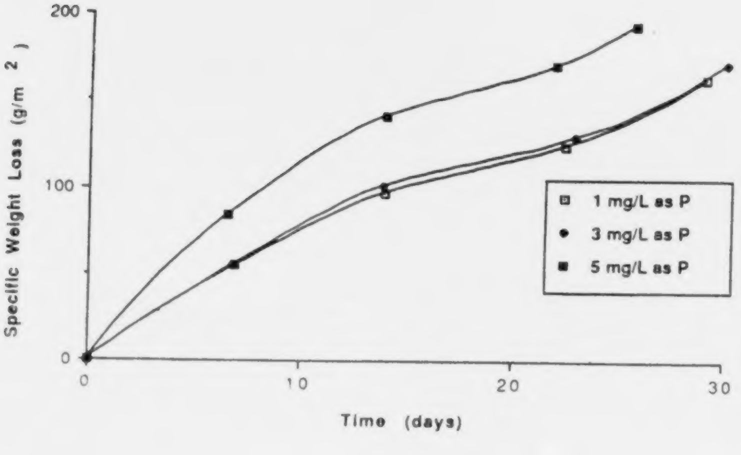


Figure 7.3.2.1
Specific Weight Losses Versus Time for Ductile Iron Immersed in Polyphosphate Treated Waters



set of each concentration are compared, using the paired t-test at a 95% probability (Appendix K).

7.4.1 Copper Results

The difference between the copper corrosion rates at the different polyphosphate concentrations were not significantly different at a 95 % confidence level for most sampling dates. This is attributed to two reasons. Firstly is polyphosphate's ineffectiveness in reducing copper corrosion for the concentrations investigated. Secondly, high variance among corrosion rates of coupons belonging to the same sample sets for the different concentrations prevented statistically showing the performances as significantly different.

7.4.2 Ductile Iron Results

The difference between the ductile iron corrosion rates for the concentrations 1 mg/L and 3 mg/L as P, were not significantly different at a 95 % confidence level. However, the difference in corrosion rates for the 5 mg/L as P, in comparison to the lower concentrations was significantly different.

7.5 Corrosion rates

7.5.1 Copper Experiments

To evaluate the inhibitory performance of polyphosphate on copper corrosion at different concentrations, refer to Figure 7.5.1.1. Figure 7.5.1.1 shows copper corrosion as independent of the polyphosphate concentration for the range of concentrations investigated. Mean comparison of the corrosion rates of the different concentrations were, for

Table 7.4.1.1
Statistical Analysis of the Copper Corrosion Rate Data for the Sodium Hexametaphosphate Concentration: 5 mg/L as P

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	6.81	0.129	0.0403	0.175 to 0.101	N/A
3	13.85	0.111	0.0100	0.118 to 0.099	N/A
3	24.14	0.105	0.0251	0.128 to 0.078	N/A
3	29.94	0.098	0.0048	0.104 to 0.095	N/A

Table 7.4.1.2
Statistical Analysis of the Copper Corrosion Rate Data for the Sodium Hexametaphosphate Concentration: 3 mg/L as P

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	6.47	0.122	0.0064	0.129 to 0.116	1 Outlier
3	13.50	0.109	0.0133	0.117 to 0.093	N/A
3	24.00	0.115	0.0048	0.120 to 0.111	N/A
3	29.68	0.089	0.0053	0.093 to 0.083	N/A

Table 7.4.1.3
Statistical Analysis of the Copper Corrosion Rate Data for the Sodium Hexametaphosphate Concentration: 1 mg/L as P

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	6.76	0.135	0.0066	0.146 to 0.126	N/A
3	13.73	0.112	0.0104	0.122 to 0.102	N/A
3	24.10	0.094	0.0086	0.111 to 0.084	N/A
3	29.92	0.088	0.0028	0.091 to 0.082	N/A

Table 7.4.1.4
Mean Comparison of the Copper Corrosion Rate Data for the Different Sodium Hexametaphosphate Concentrations Using the t-Test at a 95% Probability

Time (days)	Comparison of Concentrations		
	1 mg/L to 5 mg/L	1 mg/L to 3 mg/L	3 mg/L to 5 mg/L
7	$0.253 < 2.776$ Difference is Not Significant	$2.438 < 2.776$ Difference is Not Significant	$0.296 < 2.776$ Difference is Not Significant
14	$0.120 < 2.776$ Difference is Not Significant	$0.306 < 2.776$ Difference is Not Significant	$0.207 < 2.776$ Difference is Not Significant
24	$0.715 < 2.776$ Difference is Not Significant	$3.678 > 2.776$ Difference is Significant	$0.675 < 2.776$ Difference is Not Significant
30	$3.104 > 2.776$ Difference is Significant	$0.273 < 2.776$ Difference is Not Significant	$2.171 < 2.776$ Difference is Not Significant

Table 7.4.2.1
Statistical Analysis of the Ductile Iron Corrosion Rate
Data for the Sodium Hexametaphosphate Concentration: 5 mg/L as P

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.51	12.84	0.457	13.27 to 12.36	N/A
3	13.85	10.16	0.495	10.53 to 9.60	N/A
3	21.92	7.77	0.146	7.93 to 7.64	N/A
3	25.61	7.57	0.0587	7.64 to 7.53	N/A

Table 7.4.2.2
Statistical Analysis of the Ductile Iron Corrosion Rate
Data for the Sodium Hexametaphosphate Concentration: 3 mg/L as P

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.81	8.10	0.299	8.31 to 7.76	N/A
3	13.84	7.30	0.099	7.37 to 7.19	N/A
3	22.88	5.62	0.087	5.72 to 5.56	N/A
3	30.01	5.71	0.142	5.87 to 5.62	N/A

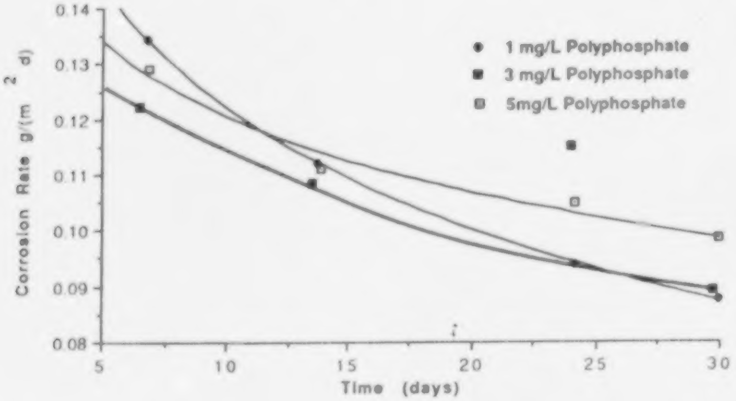
Table 7.4.2.3
Statistical Analysis of the Ductile Iron Corrosion Rate Data for the Sodium Hexametaphosphate Concentration: 1 mg/L as P

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	6.89	7.92	0.755	8.79 to 7.44	N/A
3	13.89	6.97	0.246	7.25 to 6.81	N/A
3	22.46	5.52	0.153	5.69 to 5.40	N/A
3	29.06	5.60	0.125	5.77 to 5.37	N/A

Table 7.4.2.4
Mean Comparison of the Ductile Iron Corrosion Rate Data for the Different Sodium Hexametaphosphate Concentrations Using the t-Test at a 95% Probability

Time	Comparison of Concentrations		
(days)	1 mg/L to 5 mg/L	1 mg/L to 3 mg/L	3 mg/L to 5 mg/L
7	$9.610 > 2.776$ Difference is Significant	$0.194 < 2.776$ Difference is Not Significant	$14.968 > 2.776$ Difference is Significant
14	$9.951 > 2.776$ Difference is Significant	$2.146 < 2.776$ Difference is Not Significant	$9.771 > 2.776$ Difference is Significant
22	$17.530 > 2.776$ Difference is Significant	$0.980 < 2.776$ Difference is Not Significant	$21.817 > 2.776$ Difference is Significant
26	N/A	$0.018 < 2.776$ Difference is Not Significant	N/A

Figure 7.5.1.1
Copper Corrosion Rates Versus Time for the
Sodium Hexametaphosphate Concentrations: 1, 3 & 5 mg/L as P



most sampling dates, not significantly different at a 95% confidence level. Shown in Table 7.5.1.1 are the percent differences between mean corrosion rates of each parameter setting in relation to the 1 mg/L as P concentration. Negative values indicate the corrosion rate of the concentration compared is lower.

The polyphosphate concentrations were monitored on a daily basis and the consumption for each of the tests was minimal. In fact, the polyphosphate concentrations increased slightly from liquid losses due to evaporation. The only indication to suggest the possible formation of an insoluble metal phosphate coating on copper coupons was that upon removal, the coupons had the appearance of a light yellow colour. All other parameters, such as total hardness concentration and polyphosphate consumption, had indicated otherwise.

To compare polyphosphate's performance to the controls with and without chlorine, refer to Figure 7.5.1.2. Polyphosphate reduced copper corrosion in comparison to the controls, with and without chlorine, for the range of concentrations investigated. Polyphosphate, regardless of concentration, reduced copper corrosion (>30d) in comparison to the control without chlorine by 38%, and by 22% in comparison to the control with chlorine.

7.5.2 Ductile Iron Results

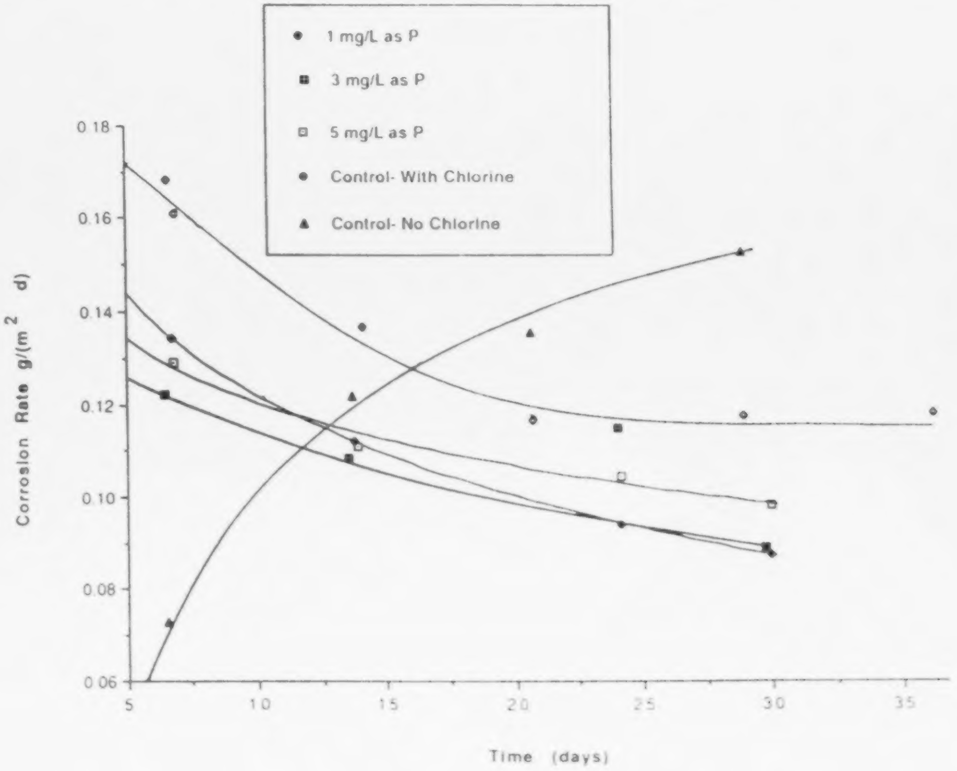
To evaluate the inhibitory performance of polyphosphate on ductile iron corrosion at different concentrations, refer to Figure 7.5.2.1. Shown in Figure 7.5.2.1, is polyphosphate, at the concentrations 1 mg/L and 3 mg/L as P, as having shown the most promise in reducing ductile iron

Table 7.5.1.1
Percent Differences Between Copper Corrosion Rates of Each Parameter Setting in Relation to the Best Setting: 1 mg/L as P

Time (days)	Average Percent Difference (%)	
	5 mg/L to 1 mg/L	3 mg/L to 1 mg/L
7	-4.4	-9.6
14	-0.9	-2.7
24	+11.7	+22.3
30	+11.4	+1.1

+ = higher
- = lower

Figure 7.5.1.2
Corrosion Rates Versus Time for Copper of the Different Sodium Hexametaphosphate Concentrations Compared to the Controls, With and Without Chlorine



corrosion. Statistically, the performance of polyphosphate at the concentrations: 1 mg/L and 3 mg/L as P, were not significantly different at a 95 % confidence level. Instead, Figure 7.5.2.1 shows ductile iron corrosion as having increased with increasing polyphosphate concentration. Ductile iron corrosion initially increased for the 5 mg/L as P concentration and the rates were, in comparison to the lower concentrations, significantly different. Shown in Table 7.5.2.1 are the percent differences between mean corrosion rates of each parameter setting in relation to the best setting, 1 mg/L as P.

The application of polyphosphate in distribution systems has been documented, in some cases, as causing the problem "red water." This phenomen was observed in tests, with the severity of the problem increasing with polyphosphate concentration. The polyphosphate concentration 5 mg/L as P, in comparison to the lower concentrations, was the worst in causing the problem "red water." "Red water" is the contamination of the water from corrosion products, producing a highly turbid reddish coloured water. This problem stems from the softening effect polyphosphate has on corrosion scales. The severity of the "red water" problem increases with increasing polyphosphate concentration. Able to soften deposits of ferric oxide, these deposits were removed and resuspended by the water's turbulent action to reduce the thickness of scale on the metal surface, producing a scale that was less protective. Visually, there was noticeable difference in the appearance and thickness in the scale growth on the surfaces of coupons exposed to the 5 mg/L as P concentration. The scale growth was noticeably less, in both density and

Figure 7.5.2.1
Ductile Iron Corrosion Rates Versus Time for the
Sodium Hexametaphosphate Concentrations: 1, 3 & 5 mg/L as P

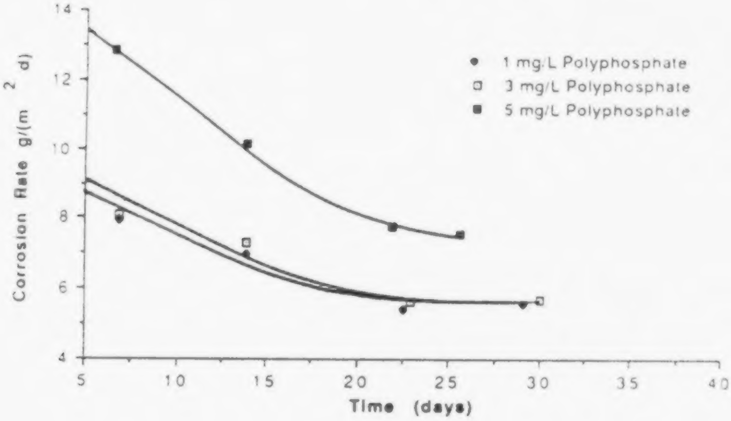


Table 7.5.2.1
Percent Differences Between Ductile Iron Corrosion Rates of Each Parameter Setting in Relation to the Best Setting: 1 mg/L as P

Time (days)	Average Percent Difference (%)	
	5 mg/L to 1 mg/L	3 mg/L to 1 mg/L
7	+62.1	+2.3
14	+45.8	+4.7
22	+25.5	+1.8

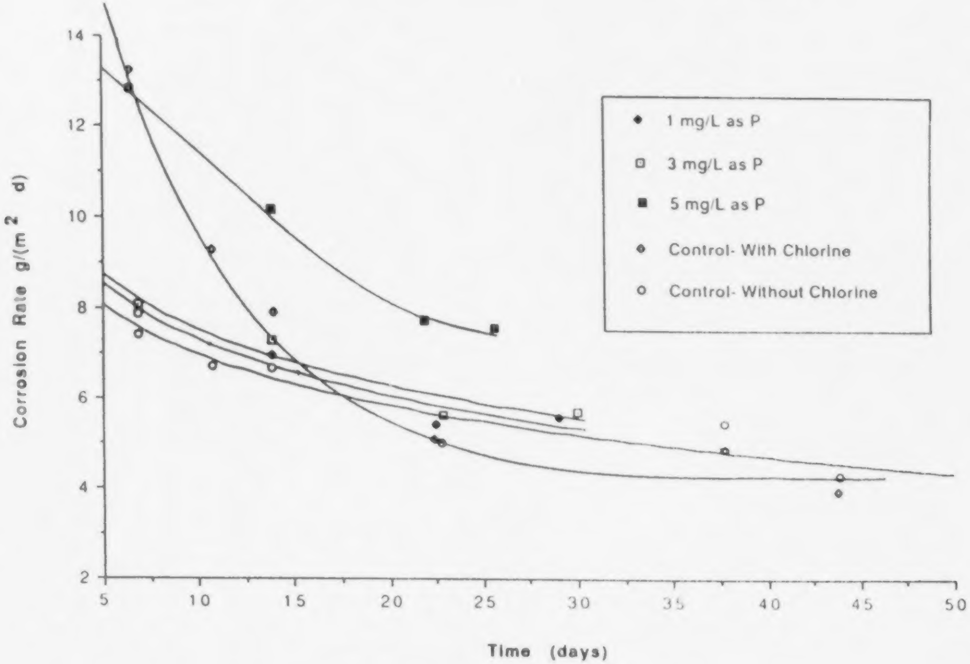
+ = higher
− = lower

thickness in comparison to scale growth for coupons exposed to the lower concentrations.

The polyphosphate concentrations were monitored on a daily basis and the consumption for each test was initially high, and later decreased with time. The greatest magnitude in consumption was for the polyphosphate concentration 5 mg/L as P. A decrease in water hardness was also observed for each setting to indicate the precipitation of polyphosphate as an insoluble metal phosphate compound. The inconsistency, however, in the magnitude by which the polyphosphate concentration fluctuated on a daily basis, shows a variability in the rate at which polyphosphate was adsorbed and that this may be attributed to the removal and addition of coupons during the experiment.

To compare polyphosphate's performance to the controls with and without chlorine, refer to Figure 7.5.2.2. Polyphosphate at the concentrations 1 mg/L and 3 mg/L as P was effective in inhibiting chlorine's initial influence for increasing corrosion. As well, the corrosion rates of the concentrations 1 mg/L and 3 mg/L as P were not significantly different in comparison to the contol without chlorine for the exposure time investigated. The 5 mg/L as P concentration was not shown to be initially beneficial in reducing ductile iron corrosion, in comparison to the control with chlorine. This is attributed to the adverse effect this concentration had on the protective properties of the corrosion scales formed on the surfaces of coupons.

Figure 7.5.2.2
Corrosion Rates Versus Time for Ductile Iron of the Different Sodium Hexametaphosphate Concentrations Compared to the Controls, With and Without Chlorine



8.0 Results For Sodium Carbonate

8.1 Methodology

The pH adjustment chemical, sodium carbonate, was evaluated at the pH settings: 7.5, 8.0, and 8.5. The control parameter was pH, and it was monitored a minimum of three times daily and adjusted when required. The experimental water was changed and chlorinated weekly. Chlorine was added to obtain a total residual concentration, following a 30 minute contact time, of approximately 1.0 mg/L.

8.2 Summary of Water Quality Changes

Tables 8.2.1 and 8.2.2 are a summary of the changes in water quality for the sodium carbonate tests. The values listed are the average change and the range by which each paramenter changed for a weekly liquid retention time. For more detailed information refer to Appendix B.

8.3 Specific Weight Loss

8.3.1 Copper Experiments

Figure 8.3.1.1 shows the specific weight losses versus time of copper using sodium carbonate at pH settings: 7.5, 8.0, and 8.5. Shown are the weight losses of copper as having decreased with increasing pH. Also shown, however, is after three weeks of exposure the weight losses of each setting increased. This suggests a similar change in the environment to each test to increase corrosion. The increase in the environment's corrosiveness may have resulted from a failed air pipe, which after being replaced, may have altered the rate of mixing to increase corrosion or

Table 8.2.1
Water Quality Summary Sheet for the Copper Experiments of the Sodium Carbonate Tests

Parameter	Control Setting					
	pH 7.5		pH 8.0		pH 8.5	
	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	14.2	10.0 to 22.6	52.3	36.8 to 77.8	123.9	113.4 to 144.0
Calcium	0.71	0.62 to 1.09	0.55	0.17 to 0.85	-0.34	-0.10 to 0.56
Chloride	3.51	3.32 to 3.81	4.03	3.02 to 6.00	3.50	2.91 to 4.33
Copper	1.00	0.55 to 1.29	0.95	0.51 to 1.36	0.74	-0.05 to 1.19
Dissolved Oxygen	11.59	11.54 to 11.64	11.62	11.58 to 11.66	11.61	11.59 to 11.63
Electrical conductivity (umhos/cm)	29.0	16.0 to 53.0	70.0	47.0 to 120.0	158.2	93.0 to 204.0
Magnesium	0.14	-0.08 to 0.36	0.12	-0.18 to 0.33	0.05	-0.21 to 0.29
Silicate	0.07	-0.02 to 0.20	0.06	-0.01 to 0.11	0.08	0.02 to 0.20
Sodium	7.25	5.00 to 11.25	24.54	17.50 to 36.30	57.14	51.30 to 65.00
Sulfate	0.32	0.00 to 0.71	0.31	-0.10 to 0.49	0.19	0.11 to 0.62
Total Hardness ($CaCO_3$)	1.5	0.1 to 2.4	-1.4	-0.2 to -2.2	-1.5	-1.2 to -2.0
Turbidity (NTU)	1.3	-0.1 to 3.1	0.6	0.0 to 0.9	0.9	0.8 to 1.3

Unless otherwise stated all values are in mg/L

Table 8.2.2
Water Quality Summary Sheet for the Ductile Iron Experiments of the Sodium Carbonate Tests

Parameter	Control Setting					
	pH 7.5		pH 8.0		pH 8.5	
	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	113.1	102.4 to 120.0	247.5	231.8 to 256.4	534.4	504.6 to 557.8
Calcium	-0.45	-0.30 to -0.50	-0.85	-0.17 to -1.26	-1.49	-0.73 to -2.48
Chloride	8.31	2.93 to 17.94	6.91	3.10 to 10.52	7.30	4.37 to 15.01
Dissolved Oxygen	11.31	11.28 to 11.34	11.28	11.26 to 11.30	11.27	11.20 to 11.32
Electrical conductivity (umhos/cm)	151.0	120.0 to 176.0	333.0	262.0 to 363.0	747.0	610.0 to 842.0
Magnesium	0.09	0.05 to 0.12	-0.02	-0.07 to 0.06	-0.07	-0.27 to 0.01
Silicate	1.40	1.03 to 1.56	1.49	0.79 to 2.20	1.46	0.94 to 2.11
Sodium	56.99	52.25 to 60.20	119.46	111.39 to 274.98	262.45	237.99 to 274.98
Sulfate	-0.61	-1.60 to -0.13	-0.62	-0.93 to -0.44	-0.82	-1.22 to -0.41
Total Hardness ($CaCO_3$)	-1.0	-1.7 to -1.0	-1.5	-2.4 to -0.9	-2.6	-4.4 to -1.0
Turbidity (NTU)	28.0	7.3 to 55.2	16.5	3.4 to 32.2	33.7	6.4 to 79.2

Unless otherwise stated all values are in mg/L

cause disturbances to cause the spalling of the corrosion scale already formed on coupons.

8.3.2 Ductile Iron Experiments

Figure 8.3.2.1 shows the specific weight losses versus time of ductile iron using sodium carbonate at pH settings: 7.5, 8.0, and 8.5. Shown are the weight losses of ductile iron as having decreased with decreasing pH. The weight losses for pH settings 8.0 and 8.5 were similar, to indicate the changes in water quality from sodium carbonate addition to maintain the desired pH's, although different, proved equally corrosive to ductile iron.

8.4 Statistical Analysis of the Corrosion Rate Data

Tables 8.4.1.1, 8.4.1.2, 8.4.1.3, 8.4.1.4, 8.4.2.1, 8.4.2.2, 8.4.2.3 and 8.4.2.4 provide a summary of the statistical analysis of the corrosion rate data for each pH setting. Included in each table is the average, standard deviation, range, and calculation of outliers using the Q-test for a 90% probability for each sample set. In addition, the means of each sample set of each concentration were compared using the paired t-test at a 95% probability.

8.4.1 Copper Results

Mean comparison of the pH settings 7.5 to 8.5 and 8.0 to 8.5 were, for most of the sampling dates, significantly different at a 95% confidence level. However, mean comparison of the pH settings 7.5 and 8.0 was, for most of the sampling dates, not significantly different. Copper corrosion decreased with increasing pH.

Figure 8.3.1.1
Specific Weight Losses Versus Time for Copper Using Sodium Carbonate at pH Settings: 7.5, 8.0 & 8.5

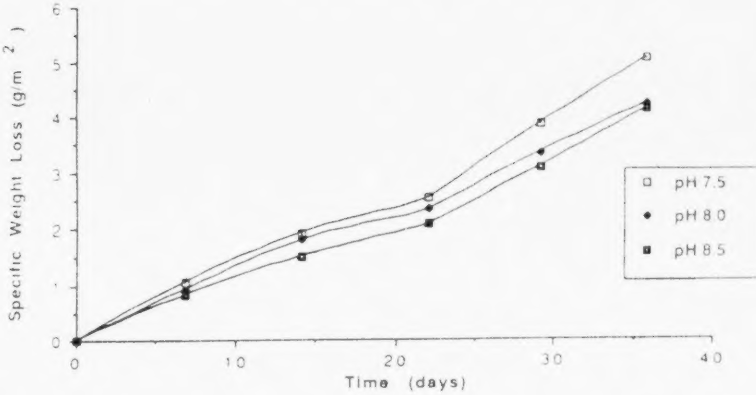


Figure 8.3.2.1
Specific Weight Losses Versus Time for Ductile Iron Using Sodium Carbonate at pH Settings: 7.5, 8.0 & 8.5

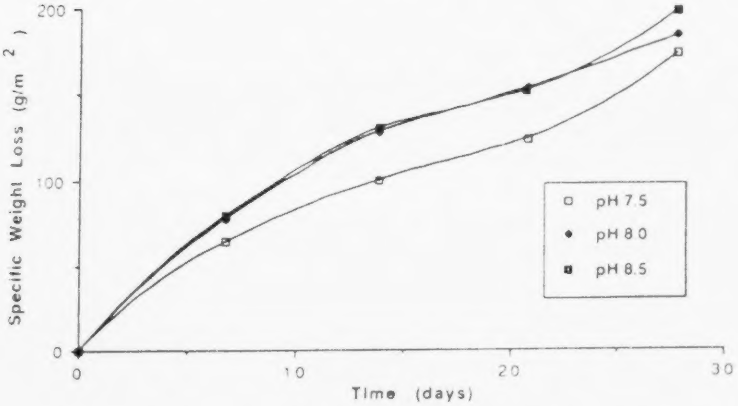


Table 8.4.1.1
Statistical Analysis of the Copper Corrosion Rate Data for pH Setting 7.5

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.82	0.157	0.0163	0.176 to 0.146	N/A
3	14.14	0.134	0.0101	0.146 to 0.129	N/A
2	22.03	0.114	0.0038	0.117 to 0.111	N/A
2	29.10	0.132	0.0015	0.133 to 0.130	N/A
2	35.89	0.141	0.0056	0.145 to 0.137	N/A

Table 8.4.1.2
Statistical Analysis of the Copper Corrosion Rate Data for pH Setting 8.0

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.85	0.137	0.00158	0.138 to 0.135	N/A
3	14.19	0.126	0.00667	0.134 to 0.122	N/A
2	22.06	0.105	0.00500	0.108 to 0.101	N/A
2	29.11	0.114	0.00028	0.114 to 0.114	N/A
2	35.89	0.117	0.01605	0.129 to 0.106	N/A

Table 8.4.1.3
Statistical Analysis of the Copper Corrosion Rate Data for pH Setting 8.5

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	6.84	0.122	0.00911	0.133 to 0.116	N/A
3	14.15	0.106	0.00765	0.113 to 0.098	N/A
2	22.02	0.093	0.00141	0.094 to 0.092	N/A
2	29.09	0.105	0.00269	0.107 to 0.104	N/A
2	35.83	0.115	0.00141	0.116 to 0.114	N/A

Table 8.4.1.4
Mean Comparison of the Copper Corrosion Rate Data for the Different pH Settings Using the t-Test at a 95% Probability

Time (days)	Comparison of pH Settings		
	7.5 to 8.0	7.5 to 8.5	8.0 to 8.5
7	$2.107 < 2.776$ Difference is Not Significant	$3.233 > 2.776$ Difference is Significant	$2.798 > 2.776$ Difference is Significant
14	$1.140 < 2.776$ Difference is Not Significant	$3.811 > 2.776$ Difference is Significant	$3.339 > 2.776$ Difference is Significant
22	$2.027 < 4.303$ Difference is Not Significant	$7.327 > 4.303$ Difference is Significant	$3.266 < 4.303$ Difference is Not Significant
29	$16.682 > 4.303$ Difference is Significant	$12.377 > 4.303$ Difference is Significant	$4.706 > 4.303$ Difference is Significant
36	$1.997 < 4.303$ Difference is Not Significant	$6.367 > 4.303$ Difference is Significant	$0.176 < 4.303$ Difference is Not Significant

Table 8.4.2.1
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH Setting 7.5

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.76	9.44	0.212	9.59 to 9.29	N/A
2	13.84	7.20	0.092	7.26 to 7.13	N/A
2	20.79	5.95	0.092	6.01 to 5.88	N/A
2	27.84	6.20	0.106	6.13 to 6.28	N/A

Table 8.4.2.2
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH Setting 8.0 - Run No. 1

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.76	12.08	0.813	11.51 to 12.66	N/A
2	13.84	9.28	0.184	9.41 to 9.15	N/A
2	20.81	7.53	0.036	7.55 to 7.50	N/A
2	27.85	6.86	0.092	6.79 to 6.92	N/A

Table 8.4.2.3
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH Setting 8.0 - Run No. 2

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.76	11.30	0.050	11.26 to 11.33	N/A
2	13.84	9.23	0.120	9.14 to9.31	N/A
2	20.81	7.37	0.010	7.36 to 7.37	N/A
2	27.85	6.58	0.014	6.59 to 6.57	N/A

Table 8.4.2.4
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH Setting 8.5

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.76	11.63	0.552	11.24 to 12.02	N/A
2	13.84	9.38	0.424	9.68 to 9.08	N/A
2	20.79	7.31	0.050	7.27 to 7.34	N/A
2	27.84	7.12	0.304	7.33 to 6.90	N/A

Table 8.4.2.5
Mean Comparison of the Ductile Iron Corrosion Rate Data for the Different pH Settings Using the t-Test at a 95% Probability

Time (days)	Comparison of pH Settings		
	7.5 to 8.0 (run #1)	7.5 to 8.5	8.0 (run #1) to 8.5
7	4.444 > 4.303 Difference is Significant	5.238 > 4.303 Difference is Significant	0.648 < 4.303 Difference is Not Significant
14	14.299 > 4.303 Difference is Significant	7.106 > 4.303 Difference is Significant	0.306 < 4.303 Difference is Not Significant
21	22.618 > 4.303 Difference is Significant	18.368 > 4.303 Difference is Significant	5.050 > 4.303 Difference is Significant
28	6.657 > 4.303 Difference is Significant	4.041 < 4.303 Difference is Not Significant	1.158 < 4.303 Difference is Not Significant

8.4.2 Ductile Iron Results

The difference between the corrosion rates of each setting were, for most of sampling dates, significantly different at a 95% confidence level. pH adjustment, between the range 7.5 to 8.5, proved ineffective in reducing ductile iron corrosion. The ductile iron corrosion rates increased with increasing pH. Only above the pH value of 10, will there be a significant reduction in ductile iron corrosion as a result of pH adjustment.

8.5 Corrosion Rates

8.5.1 Copper Experiments

To evaluate the inhibitory performance of sodium carbonate on copper corrosion between the pH range of 7.5 to 8.5, refer to Figure 8.5.1.1. Figure 8.5.1.1 shows copper corrosion, taking into account the water quality changes for the liquid's weekly retention time, as decreasing with increasing pH. The pH setting 8.5 showed the most promise in reducing copper corrosion and, as well, was affected most for changes in water quality. Shown in Table 8.5.1.1 are the percent differences between mean corrosion rates of each pH setting in relation to the best setting, pH 8.5.

To evaluate the performance of sodium carbonate in reducing copper corrosion, in comparison to the controls with and without chlorine, refer to Figure 8.6.1.2. Sodium carbonate was effective at all three pH settings in reducing initial corrosion with the most significant decrease occurring for pH setting 8.5 in comparison to the control without chlorine. Sodium carbonate was, to a lesser magnitude, only initially effective in

Figure 8.5.1.1
Copper Corrosion Rates Versus Time for
Sodium Carbonate at pH Settings: 7.5, 8.0 & 8.5

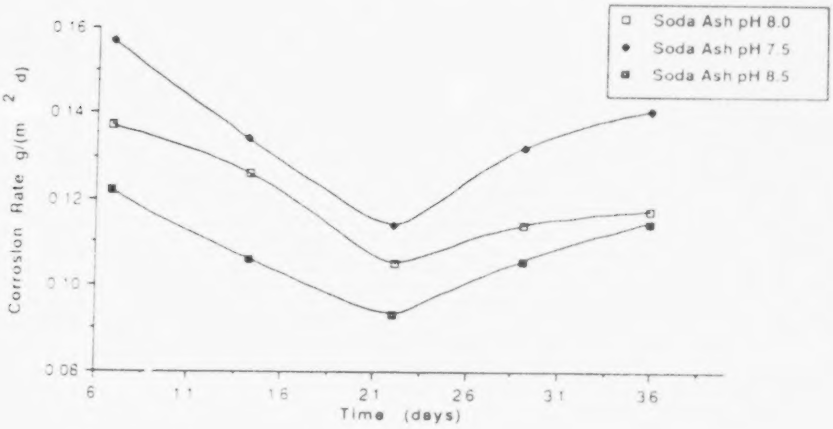
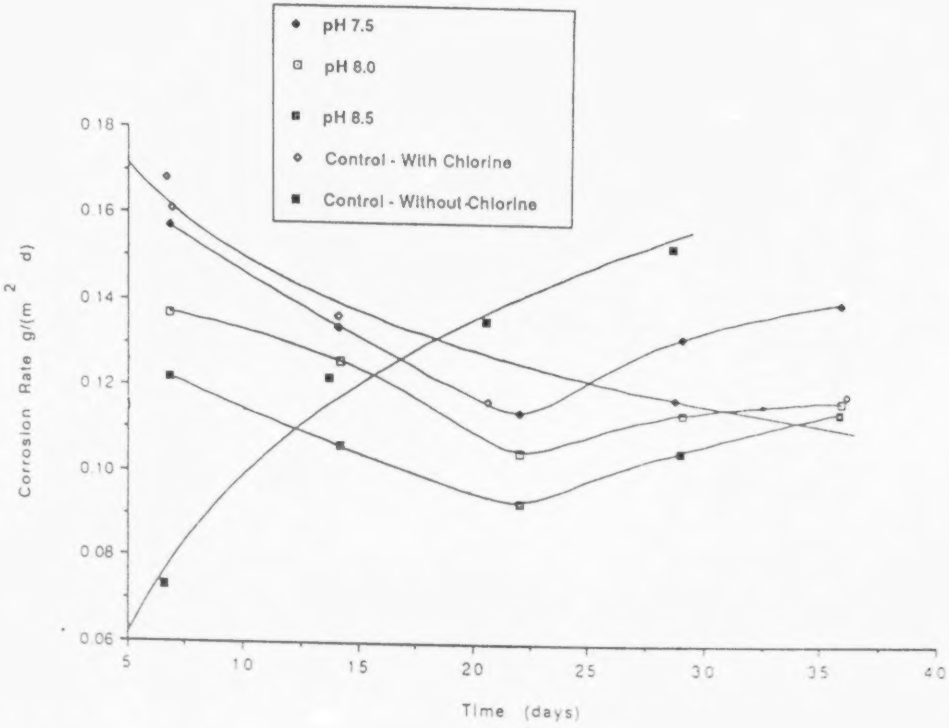


Table 8.5.1.1
Percent Differences Between Copper Corrosion Rates of Each Parameter Setting in Relation to the Best Setting: pH 8.5

Time (days)	Average Percent Difference (%)	
	pH 7.5 to pH 8.5	pH 8.0 to pH 8.5
7	+28.7	+12.3
14	+26.4	+18.9
22	+22.6	+12.9
29	+25.7	+8.6
36	+22.6	+1.7

+ = higher
– = lower

Figure 8.5.1.2
Corrosion Rates Versus Time for Copper at Different pH
Settings Compared to the Controls With and Without Chlorine



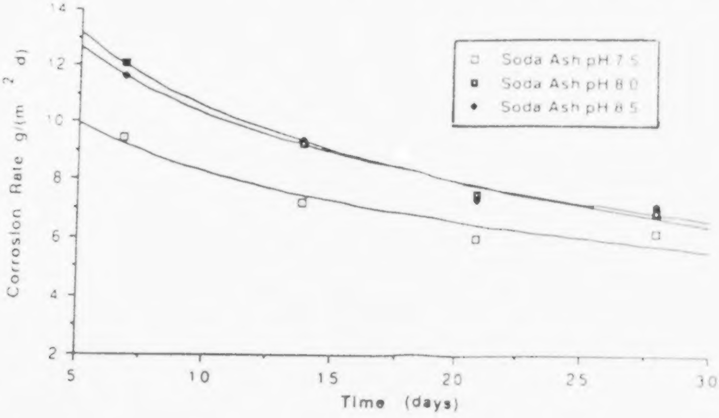
reducing corrosion for all three pH settings in comparison to the control with chlorine. The corrosion rates for sodium carbonate were observed to increase after 25 days of exposure for all three pH settings, and this increase maybe attributed to the explanation given in section 8.3.1.

8.5.2 Ductile Iron Experiments

To evaluate the inhibitory performance of sodium carbonate on ductile iron corrosion between the pH range of 7.5 to 8.5, refer to Figure 8.5.2.1. Before drawing conclusions from Figure 8.5.2.1, the changes in water quality as a result of having performed these tests using batch reactors must be considered. Evaluating pH adjustment chemicals under batch conditions compounded by the fact that the solution water was aerated, caused significant changes in water quality to the experimental water. The amount of change in water quality to the experimental water was dependent on the desired pH setting. That is, maintaining the higher pH settings produced greater changes in water quality of the experimental water.

By the process of aeration, carbon dioxide, on a continuous basis, was added to the experimental water. The reaction of carbon dioxide with water served to increase the total carbonic concentration and the acidity of the solution (Loeventhal & Marais, 1976). However, carbon dioxide addition does not cause a net increase in alkalinity. The effect of changing the total carbonic concentration was to gradually decrease with time the pH of the experimental water. To counter this gradual decrease in pH, required the addition of sodium carbonate on a regular basis to return the pH to its desired setting. Each time sodium carbonate was added, increases

Figure 8.5.2.1
Ductile Iron Corrosion Rates Versus Time for
Sodium Carbonate at pH Settings: 7.5, 8.0 & 8.5



occurred in alkalinity, total carbonic concentration and electrical conductivity.

The result of these water quality changes to the experimental water was to intensify the electrochemical process for corrosion. For example, increasing the electrical conductivity of the water intensified the transfer of electrolytic current in the form of ions in solution. The effect of increasing alkalinity was to possibly affect the type and quality of protection offered by corrosion scales formed on the metal's surface. During cleaning, it was observed that coupons exposed to high alkalinity waters (pH settings 8.0 and 8.5) had a scale growth that was both softer and more easily removed. This suggests having substantially increased alkalinity, as was the case for pH settings 8.0 and 8.5, may have possibly affected the type of corrosion scale deposited on the metal's surface. For example, ferrous iron undergoes the secondary reaction to form ferric hydroxide for high pH, low alkalinity waters and will produce a scale that is both soft and permeable. In low pH, high carbonate waters, the scale siderite ($FeCO_3$) readily forms to produce a durable, dense scale that retains its crystal structure for better protection. The scale ferric hydroxide offers less resistance to the transfer of oxygen to the metal's surface and as a result, is less protective in comparison to the scale $FeCO_3$ (siderite).

Reconsidering Figure 8.5.2.1, the effect of having substantially changed the water quality of the experimental water further increased the water's corrosivity. Shown in Figure 8.5.2.1 is ductile iron corrosion as having increased with increasing pH. Shown in Table 8.5.2.1 are the percent differences between mean corrosion rates of each pH setting in relation to the best setting, pH 7.5.

Table 8.5.2.1
Percent Differences Between Ductile Iron Corrosion Rates of Each Parameter Setting in Relation to the Best Setting: pH 7.5

Time (days)	Average Percent Difference (%)	
	pH 8.5 to pH 7.5	pH 8.0 to pH 7.5
7	+23.2	+19.7
14	+30.3	+28.2
21	+22.9	+23.9
28	+14.8	+6.1

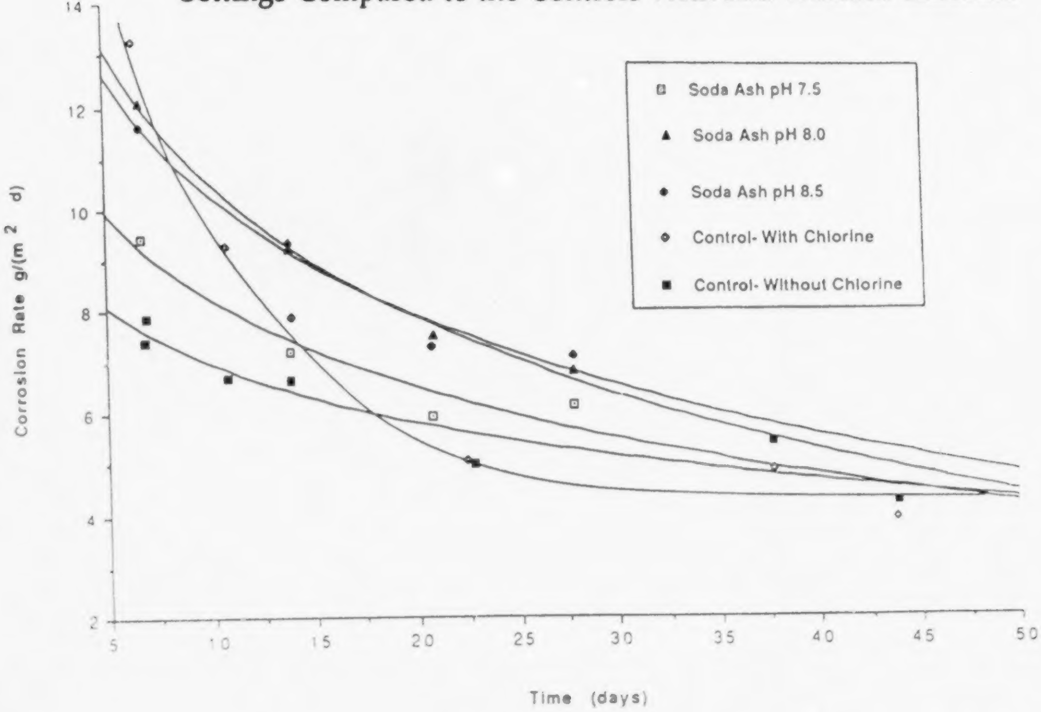
+ = higher
− = lower

In addition, further increases in water quality changes beyond the pH setting 8.0 did not further increase corrosion. That is, the corrosion rates for pH settings 8.0 and 8.5 were not significantly different for the exposure time investigated.

Additional lab work was performed to determine the water quality change that would have occurred if the water was treated only once, that which would be the case for in-situ operation. Results were that the total alkalinity change to adjust the water to the pH setting 8.5 would only increase the alkalinity of the raw water by an additional 5 mg/L as $CaCO_3$. This small change in alkalinity is not considered enough to cause there to be a significant difference in the rates of corrosion for in-situ performance for the different pH settings. Therefore, it is likely the corrosion rates would probably be similar to the rates reported in Phase 1 of the in-situ study.

To compare the performance of sodium carbonate, taking into account the changes in water quality, to the controls with and without chlorine, refer to Figure 8.6.2.2. The pH settings 8.0 and 8.5 were not effective in reducing ductile iron corrosion as a result of water quality changes. The pH setting 7.5, least affected for changes in water quality, was initially effective in reducing by 50% chlorine's initial influence on corrosion. This initial, positive response from pH setting 7.5 is possibly attributed to the large increase in bicarbonate concentration versus the small change in hydroxide concentration, to assist in promoting the secondary reaction of ferrous iron to siderite ($FeCO_3$) to deposit a good protective layer. In testing sodium carbonate, the pH setting 7.5 showed the most promise. Although, with respect to the inhibitory performance of

Figure 8.5.2.2
Corrosion Rates Versus Time for Ductile Iron at Different pH Settings Compared to the Controls With and Without Chlorine



the other chemicals, sodium carbonate at this pH setting and the observed water quality changes was least effective.

9.0 Results For the pH Adjustment Chemical: Sodium Hydroxide.

9.1 Methodology

The pH adjustment chemical, sodium hydroxide, was evaluated at the pH settings: 7.5, 8.0, and 8.5. The control parameter was pH, and was monitored a minimum of three times daily and adjusted when required. The experimental water was changed and chlorinated weekly. Chlorine was added to obtain a total residual concentration, following a 30 minute contact time, of approximately 1.0 mg/L.

9.2 Summary of Water Quality Changes

Tables 9.2.1 and 9.2.2 are a summary of the changes in water quality for the sodium hydroxide tests. The values listed are the average change and the range by which each paramenter changed for a weekly liquid retention time. For more detailed information refer to Appendix C.

9.3 Specific Weight Loss

9.3 1 Copper Experiments

Figure 9.3.1.1 shows the specific weight losses with time for copper using sodium hydroxide at pH settings: 7.5, 8.0, and 8.5. Shown, are the specific weight losses decreasing with time with increasing pH.

Table 9.2.1
Water Quality Summary Sheet for the Copper Experiments of the Sodium Hydroxide Tests

Parameter	Control Setting					
	pH 7.5		pH 8.0		pH 8.5	
	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	5.5	5.1 to 5.7	32.5	29.1 to 37.1	108.0	99.7 to 121.5
Calcium	0.59	0.48 to 0.84	0.68	0.32 to 1.38	0.45	0.29 to 0.62
Chloride	5.19	3.12 to 10.26	5.26	2.16 to 10.06	5.78	3.00 to 10.06
Copper	1.17	0.77 to 1.43	0.98	0.71 to 1.16	0.74	0.53 to 0.85
Dissolved Oxygen	11.61	11.58 to 11.64	11.65	11.63 to 11.68	11.64	11.60 to 11.66
Electrical conductivity (umhos/cm)	16.5	15.0 to 18.0	52.3	46.0 to 59.0	149.0	125.0 to 169.0
Magnesium	0.14	0.09 to 0.22	0.10	0.04 to 0.14	0.08	0.02 to 0.17
Silicate	0.06	-0.01 to 0.14	0.13	0.04 to 0.23	0.09	0.02 to 0.18
Sodium	3.16	2.49 to 3.78	16.08	14.46 to 17.80	52.06	47.03 to 58.96
Sulfate	0.39	0.07 to 0.52	0.28	-0.01 to 0.64	0.32	0.12 to 0.60
Total Hardness ($CaCO_3$)	1.3	0.0 to 1.8	1.1	0.2 to 2.2	1.6	0.6 to 2.6
Turbidity (NTU)	1.3	-0.1 to 3.1	0.6	0.0 to 0.9	0.9	0.8 to 1.3

Unless otherwise stated all values are in mg/L.

Table 9.2.2
Water Quality Summary Sheet for the Ductile Iron Experiments of the Sodium Hydroxide Tests

Parameter	Control Setting					
	pH 7.5		pH 8.0		pH 8.5	
	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	145.4	125.4 to 177.2	238.5	218.4 to 266.4	476.2	455.4 to 487.2
Calcium	0.58	-0.63 to 2.01	-0.67	-2.19 to 1.45	-1.40	-2.13 to -0.53
Chloride	9.11	2.15 to 15.62	3.81	1.93 to 11.68	6.33	1.05 to 10.28
Dissolved Oxygen	11.26	11.23 to 11.29	11.24	11.18 to 11.28	11.24	11.18 to 11.28
Electrical conductivity (umhos/cm)	173.7	159.0 to 189.0	264.8	235.0 to 295.0	607.3	571.0 to 661.0
Iron	3.18	1.29 to 4.21	0.85	0.02 to 2.28	0.84	0.60 to 1.01
Magnesium	-0.19	-0.41 to -0.31	-0.20	-0.41 to -0.04	-0.41	-0.50 to -0.30
Silicate	1.32	1.02 to 1.65	1.20	0.74 to 1.76	0.84	0.60 to 1.01
Sodium	69.11	58.29 to 81.92	108.84	98.31 to 120.64	224.40	222.40 to 225.55
Sulfate	-1.56	-2.15 to -1.23	-1.29	-3.15 to -0.64	-1.75	-2.35 to -1.19
Total Hardness ($CaCO_3$)	3.1	-1.0 to 10.2	-1.5	-8.5 to 2.6	0.6	-1.3 to 4.0
Turbidity (NTU)	8.6	4.3 to 11.6	5.1	2.1 to 9.7	7.6	3.9 to 10.0

Unless otherwise stated all values are in mg/L

9.3.2 Ductile Iron Experiments

Figure 9.3.2.1 shows the specific weight losses with time of ductile iron using sodium hydroxide at pH settings: 7.5, 8.0, and 8.5. Unlike the copper results, there was little difference between the specific weight lossesof ductile iron at the different pH settings. As previously discussed, a significant reduction in the corrosion of ferrous metals occurs only when the water's pH is above 10, or when pH adjustment causes the precipitation of $CaCO_3$ to form a protective coating to inhibit corrosion. For each setting, the specific weight loss increased uniformly and similar were the rates to indicate pH adjustment by sodium hydroxide for the pH range investigated was not inhibiting corrosion.

9.4 Statistical Analysis of Corrosion Rate Data

Tables 9.4.1.1, 9.4.1.2, 9.4.1.3, 9.4.1.4, 9.4.2.1, 9.4.2.2, 9.4.2.3 and 9.4.2.4 provide a summary of the statistical analysis of the corrosion rate data for each pH setting. Included in each table is the average, standard deviation, range, and calculation of outliers using the Q-test for a 90% probability for each sample set. In addition, the means of each sample set for each pH setting were compared using the paired t-test at a 95% probability.

9.4.1 Copper Results

Mean comparison of the pH settings 7.5 to 8.5 and 8.0 to 8.5 were, for several sampling dates, significantly different at a 95% confidence level. Where as mean comparison of the pH setting 7.5 to 8.0 was, for the first two weeks, significantly different. The difficultly in statistically showing there to be a difference between pH settings, if any, is attributed to small

Figure 9.3.1.1
Specific Weight Losses Versus Time of Copper Using Sodium Hydroxide at Different pH Settings

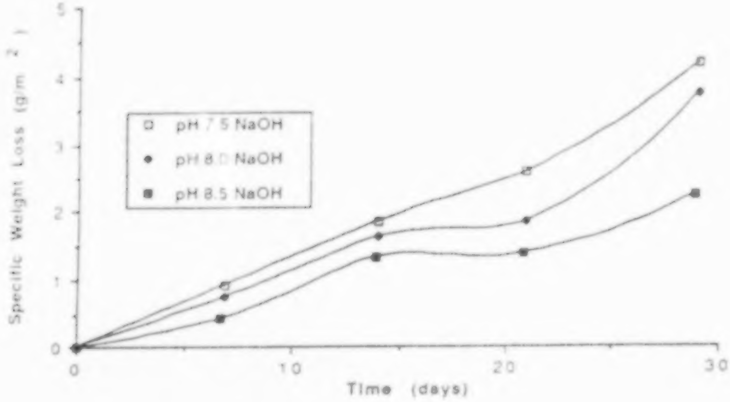


Figure 9.3.2.1
Specific Weight Losses Versus Time of Ductile Iron Using Sodium Hydroxide at Different pH Settings

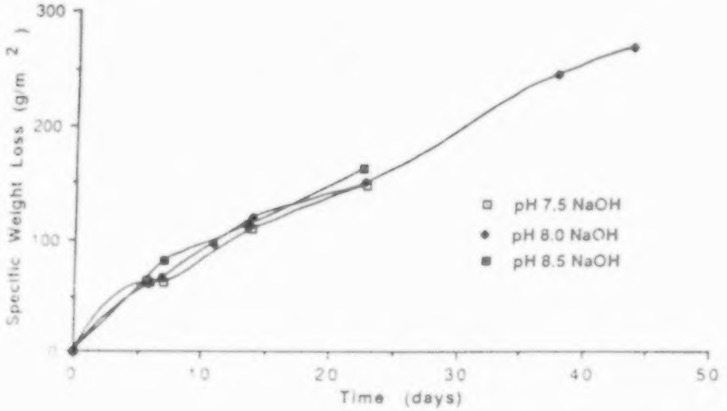


Table 9.4.1.1
Statistical Analysis of the Copper Corrosion Rate Data for pH Setting 8.5

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.73	0.065	0.01838	0.078 to 0.052	N/A
2	13.81	0.096	0.00283	0.098 to 0.094	N/A
2	20.84	0.067	0.00781	0.072 to 0.061	N/A
3	28.88	0.078	0.01332	0.089 to 0.063	N/A

Table 9.4.1.2
Statistical Analysis of the Copper Corrosion Rate Data for pH Setting 8.0

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.85	0.111	0.0064	0.115 to 0.106	N/A
2	13.93	0.116	0.0010	0.116 to 0.115	N/A
2	20.93	0.089	0.0050	0.092 to 0.085	N/A
4	29.00	0.129	0.0046	0.135 to 0.125	N/A

Table 9.4.1.3
Statistical Analysis of the Copper Corrosion Rate Data for pH Setting 7.5

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.89	0.136	0.0010	0.136 to 0.135	N/A
2	13.97	0.133	0.0010	0.133 to 0.132	N/A
2	20.94	0.124	0.0188	0.132 to 0.115	N/A
4	29.02	0.144	0.0081	0.155 to 0.137	N/A

Table 9.4.1.4
Mean Comparison of the Copper Corrosion Rate Data for the Different pH Settings Using the t-Test at a 95% Probability

Time	Comparison of pH Settings		
(days)	7.5 to 8.0	7.5 to 8.5	8.0 to 8.5
7	$5.458 > 4.303$ Difference is Significant	$5.455 > 4.303$ Difference is Significant	$3.343 < 4.303$ Difference is Not Significant
14	$17.000 > 4.303$ Difference is Significant	$17.433 > 4.303$ Difference is Significant	$9.423 > 4.303$ Difference is Significant
21	$2.544 < 4.303$ Difference is Not Significant	$3.960 < 4.303$ Difference is Not Significant	$3.355 < 4.303$ Difference is Not Significant
29	$3.221 > 2.571$ Difference is Significant	$8.227 > 2.571$ Difference is Significant	$7.300 > 2.571$ Difference is Significant

Table 9.4.2.1
Statistical Analysis of the Ductile iron Corrosion Rate Data for pH Setting 8.5

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	5.59	11.52	0.503	12.09 to 11.13	N/A
3	13.56	8.32	0.535	8.93 to 7.92	N/A
3	22.44	7.24	0.204	7.39 to 7.01	N/A
2	6.97	11.76	0.877	12.38 to 11.14	N/A

Table 9.4.2.2
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH Setting 8.0

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	5.77	10.39	0.0345	10.43 to 10.37	N/A
3	13.84	8.62	0.256	8.91 to 8.44	N/A
3	22.68	6.62	0.121	6.71 to 6.48	N/A
2	6.88	9.69	0.304	9.90 to 9.47	N/A
2	10.79	9.01	0.163	9.12 to 8.89	N/A
2	37.76	6.46	0.184	6.59 to 6.33	N/A
2	43.79	6.13	0.036	6.16 to 6.11	N/A

Table 9.4.2.3
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH Setting 7.5

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	5.89	10.67	0.180	10.80 to 10.54	1 Outlier
3	13.89	7.86	0.010	7.87 to 7.86	1 Outlier
3	22.71	6.51	0.060	6.57 to 6.46	N/A
2	6.94	8.97	0.060	8.93 to 9.01	N/A

Table 9.4.2.4
Mean Comparison of the Ductile Iron Corrosion Rate Data for the Different pH Settings Using the t-Test at a 95% Probability

Time	Comparison of pH Settings		
(days)	7.5 to 8.0	7.5 to 8.5	8.0 to 8.5
6	2.634 < 2.776 Difference is Not Significant	2.744 < 2.776 Difference is Not Significant	3.865 > 2.776 Difference is Significant
14	5.116 > 2.776 Difference is Significant	1.483 < 2.776 Difference is Not Significant	0.812 < 2.776 Difference is Not Significant
23	1.405 < 2.776 Difference is Not Significant	5.921 > 2.776 Difference is Significant	4.508 > 2.776 Difference is Significant
7	3.286 < 4.303 Difference is Not Significant	4.489 > 4.303 Difference is Significant	3.154 < 4.303 Difference is Not Significant

sample sets compounded with high data variance. However, the tendency of the data was copper corrosion decreased with increasing pH.

9.4.2 Ductile Iron Results

Mean comparison of the pH settings 7.5 to 8.5 and 8.0 to 8.5 were, for several sampling dates, significantly different at a 95% confidence level. However, mean comparison of the pH setting 7.5 to 8.0 was, for most sampling dates, not significantly different. Similar to the sodium carbonate results, ductile iron corrosion increased with increasing pH. pH adjustment, between the range 7.5 to 8.5, proved ineffective in reducing ductile iron corrosion. Only above the pH value of 10, will there be a significant reduction in ductile iron corrosion for pH adjustment of a soft water.

9.5 Corrosion Rates

9.5.1 Copper Experiments

To evaluate the inhibitory performance of sodium hydroxide on copper corrosion between the pH range of 7.5 to 8.5, refer to Figure 9.5.1.1. Mean comparison of the pH settings 7.5 to 8.5 and 8.0 to 8.5 were, for several sampling dates, significantly different for a 95% confidence level. The tendency, taking into account the water quality changes for the liquid's retention time, is that increasing alkalinity, pH, and electrical conductivity reduces copper corrosion. Shown in Table 9.5.1.1 are the percent differences in the mean corrosion rates of each pH setting in relation to the best setting, pH 8.5. A 50% reduction in copper corrosion was observed from increasing the pH from 7.5 to 8.5.

Figure 9.5.1.1
Copper Corrosion Rates Versus Time for Sodium Hydroxide at pH Settings: 7.5, 8.0 & 8.5

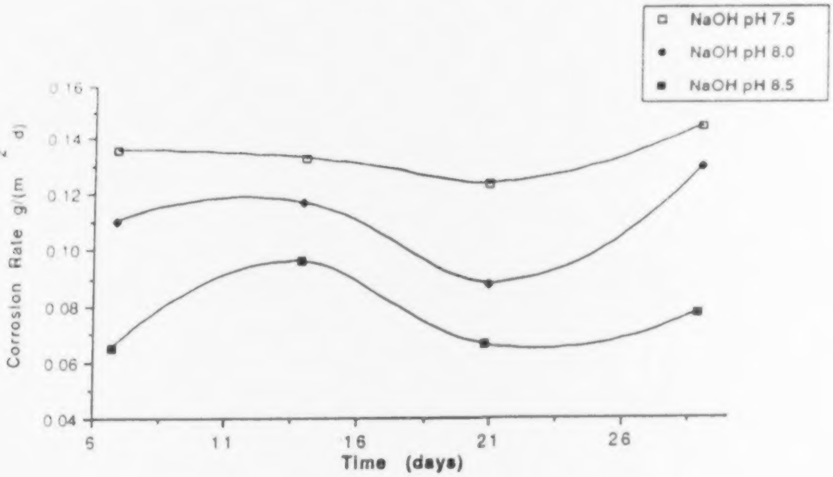


Table 9.5.1.1
Percent Differences Between Copper Corrosion Rates
of Each Parameter Setting in Relation to the Best Setting: pH 8.5

Time (days)	Average Percent Difference (%)	
	pH 7.5 to pH 8.5	pH 8.0 to pH 8.5
7	+109.2	+70.8
14	+38.5	+20.8
21	+32.8	+85.1
29	+65.4	+84.6

+ = higher
- = lower

The results of this study are in agreement to those suggested in the literature. The changes in water quality associated with the desired pH settings were favorable for promoting the growth of a thick, protective cuprous oxide film. Increasing both alkalinity and electrical conductivity intensified electronic and ionic conduction needed for the formation of a good protective cuprous oxide film (AWWA, 1985).

To evaluate the performance of sodium hydroxide for inhibiting copper corrosion in comparison to the controls with and without chlorine, refer to Figure 9.5.1.5. Shown, is copper corrosion decreasing with increasing pH. The most significant decrease was for the pH setting 8.5 for a 50% and 34% reduction in copper corrosion in comparison to controls with and without chlorine. Copper corrosion is pH dependent (AWWA, 1985) and the results have indicated this. The pH setting 8.5, and its associated water quality changes, showed the most promise in reducing copper corrosion.

9.5.2 Ductile Iron Results

To evaluate the inhibitory performance of sodium hydroxide on ductile iron corrosion between the pH range of 7.5 to 8.5, refer to Figure 9.5.2.1. The results of the sodium hydroxide tests were very similar to those results obtained in testing sodium carbonate. Changes in water quality of experimental waters of the sodium hydroxide tests were similar those observed in testing sodium carbonate. The only major difference between the water quality changes was that the addition of sodium hydroxide did not directly increase the total carbonic concentration. Rather, the addition of sodium hydroxide caused increases in the

Figure 9.5.1.2
Corrosion Rates Versus Time for Copper at Different pH Settings Compared to the Controls With and Without Chlorine

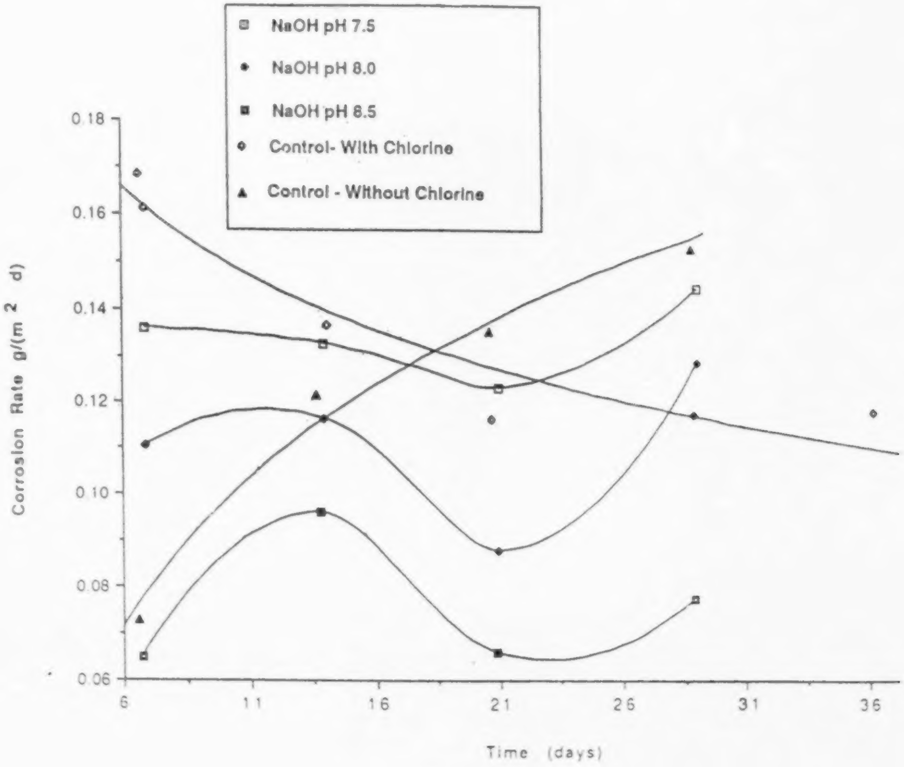
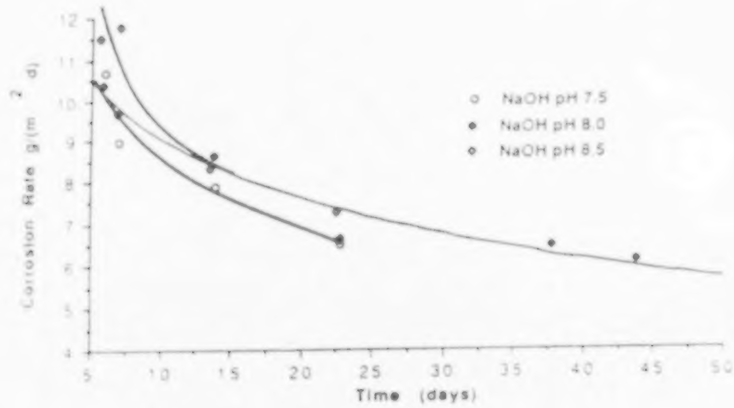


Figure 9.5.2.1
Ductile Iron Corrosion Rates Versus Time for Sodium Hydroxide at pH Settings: 7.5, 8.0 & 8.5



hydroxide ion concentration and electrical conductivity. The changes however, were similar in magnitude to that of the sodium carbonate tests.

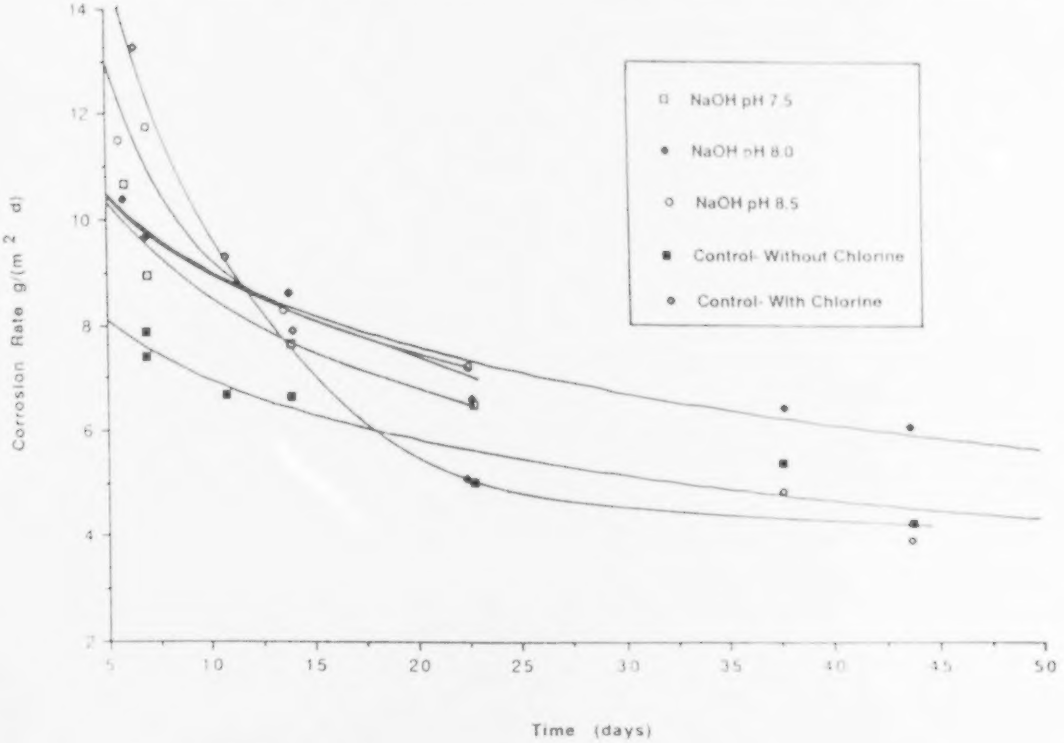
Conclusions, for the performance of sodium hydroxide in reducing ductile iron corrosion, are similar to those assessed for sodium carbonate tests. Attempts to maintain pH at its desired settings through the periodic addition of sodium hydroxide, resulted in significant changes in water quality which served to enhance the electrochemical process for corrosion. Similar to the sodium carbonate results, is that above the pH setting 8.0, further additional changes in water quality did not further increase corrosion. The pH setting of 7.5 proved to be the most promising. Shown in Table 9.5.2.1 are the percent differences in the mean corrosion rates of each pH setting in relation to the best setting, pH 7.5. Both sodium hydroxide and sodium carbonate are pH adjustment chemicals. The ineffectiveness of sodium hydroxide is subject to the same limitations given for sodium carbonate.

In comparison to the controls with and without chlorine, Figure 9.5.2.2 shows sodium hydroxide as only slightly effective in reducing chlorine's initial influence. The pH setting of 7.5, least affected by changes in water quality, showed the most promise in reducing corrosion. With respect to the inhibitory performance of the other chemicals, sodium hydroxide was less effective.

Table 9.5.2.1
Percent Differences Between Ductile Iron Corrosion Rates of Each Parameter Setting in Relation to the Best Setting: pH 7.5

Time (days)	Average Percent Difference (%)	
	pH 8.5 to pH 7.5	pH 8.0 to pH 7.5
6	+8.0	-2.6
14	-5.9	+9.7
23	+11.2	+1.7

Figure 9.5.2.2
Corrosion Rates Versus Time for Ductile Iron at Different pH Settings Compared to the Controls With and Without Chlorine



10.0 Results For Lime, Carbon Dioxide, and Sodium Hydroxide

10.1 Methodology

The conditioning chemical, lime, added as $Ca(OH)_2$, was evaluated together with carbon dioxide and sodium hydroxide. The control parameters investigated for their influence on corrosion were pH and total hardness. Control parameter settings were as follows: pH settings investigated were 7.5, 8.0, and 8.5. Total hardness concentrations investigated were 25, 50, and 75 mg/L as $CaCO_3$. Both control parameters were monitored daily and adjusted when required. Table 10.1.1 lists the combinations for the control parameters for the settings investigated.

Yellowknife's river water has a total hardness concentration of less than 20 mg/L as $CaCO_3$. The amount of calcium contributing to this total hardness averaged 14 mg/L as $CaCO_3$. Table 10.1.2 summarizes the amount of lime, as $Ca(OH)_2$, needed to increase the total hardness concentration to the desired settings.

Each conditioning chemical was added to serve a particular purpose. For example, the addition of lime served to equally increase both hardness and alkalinity. The addition of carbon dioxide served to lower the pH to the desired setting, following lime addition. The addition of sodium hydroxide served to maintain the desired pH settings, as well as to add alkalinity. The experimental water was changed and chlorinated weekly to obtain a total residual chlorine concentration, following a 30 minute contact time, of approximately 1.0 mg/L.

Table 10.1.1
Total Hardness and pH Combinations for the Different Control Settings Investigated

pH	Total Hardness (mg/L as $CaCO_3$)		
	25	50	75
7.5	X		X
8.0		X	
8.5	X		X

Table 10.1.2
Lime Additions, as $Ca(OH)_2$, Needed to Increase the Water's Total Hardness Concentration to the Following Concentrations: 25, 50 and 75 mg/L as $CaCO_3$

Desired Hardness (mg/L as $CaCO_3$)	Lime Added (mg/L as $Ca(OH)_2$)	Total Calcium Concentration (mg/L as $CaCO_3$)
25	3.7	19
50	22.2	44
75	40.7	69

10.2 Summary of Water Quality Changes

Tables 10.2.1 and 10.2.2 are a summary of the changes in water quality for the lime tests. The values listed are the average change and the range by which each paramenter changed for a weekly liquid retention time. For more detailed information refer to Appendix D.

10.3 Specific Weight Loss

10.3.1 Copper Experiments

Figure 10.3.1.1 shows the specific weight losses of copper using lime, carbon dioxide, and sodium hydroxide at different pH and hardness settings. Increasing both pH and alkalinity was of greater benefit in reducing copper corrosion, than by increasing the hardness concentration.

10.3.2 Ductile Iron experiments

Figure 10.3.2.1 shows the specific weight losses of ductile iron using lime, carbon dioxide, and sodium hydroxide at different pH and hardness settings. Shown is Ductile iron corrosion having decreased with decreasing pH and increasing hardness concentration.

Table 10.2.1
Water Quality Summary Sheet for the Copper Experiments of the Lime Tests

Parameter	Control Setting									
	pH 7.5, Hardness 75 mg/L $CaCO_3$		pH 8.0, Hardness 50 mg/L $CaCO_3$		pH 8.5, Hardness 75 mg/L $CaCO_3$		pH 7.5, Hardness 25 mg/L $CaCO_3$		pH 8.5, Hardness 25 mg/L $CaCO_3$	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	109.4	91.8 to 113.4	242.9	215.4 to 257.8	507.5	422.4 to 584.5	5.5	5.1 to 5.7	108.0	99.7 to 121.5
Chloride	4.17	1.76 to 6.87	2.33	1.99 to 2.55	3.67	2.67 to 5.48	5.19	3.12 to 10.26	5.78	3.00 to 12.66
Copper	0.67	0.18 to 1.66	0.50	0.12 to 1.04	0.33	0.22 to 0.58	1.17	0.77 to 1.43	0.74	0.53 to 0.85
Dissolved Oxygen	11.62	11.55 to 11.68	11.63	11.55 to 11.67	11.64	11.62 to 11.68	11.61	11.58 to 11.64	11.64	11.60 to 11.66
Electrical Conductivity (umhos/cm)	146.8	117.0 to 155.0	323.8	252.0 to 375.0	730.5	532.0 to 885.0	16.5	15.0 to 18.0	149.0	125.0 to 169.0
Magnesium	0.08	-0.02 to 0.23	-0.03	-0.07 to 0.02	-0.19	-0.26 to -0.10	0.14	0.09 to 0.22	0.08	0.02 to 0.17
Silicate	0.11	0.02 to 0.25	0.01	0.02 to 0.12	0.02	0.02 to 0.15	0.06	-0.01 to 0.14	0.09	0.02 to 0.18
Sodium	25.66	15.04 to 37.14	98.37	92.43 to 104.55	226.99	187.63 to 250.11	53.71	45.48 to 66.15	149.87	44.98 to 198.49
Sulfate	-0.33	-1.20 to 0.08	-0.16	-0.71 to 0.28	-0.46	-1.16 to 0.16	0.39	0.07 to 0.52	0.32	0.12 to 0.60
Total Hardness ($CaCO_3$)	-0.8	-7.4 to 3.9	-2.4	-1.7 to 4.0	-12.4	-14.8 to -7.7	1.3	0.0 to 1.8	1.6	0.6 to 2.6
Turbidity (NTU)	0.3	0.0 to 0.7	0.7	0.1 to 1.8	0.3	-0.2 to 0.8	0.7	0.1 to 1.3	0.1	-0.5 to 0.6

Unless otherwise stated all values are in mg/L

Table 10.2.2
Water Quality Summary Sheet for the Ductile Iron Experiments of the Lime Tests

Parameter	Control Setting									
	pH 7.5, Hardness 75 mg/L $CaCO_3$		pH 8.0, Hardness 50 mg/L $CaCO_3$		pH 8.5, Hardness 75 mg/L $CaCO_3$		pH 7.5, Hardness 25 mg/L $CaCO_3$		pH 8.5, Hardness 25 mg/L $CaCO_3$	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	122.0	73.9 to 177.8	212.8	155.9 to 263.2	374.3	280.7 to 482.3	94.7	68.4 to 131.0	313.5	97.8 to 408.6
Chloride	4.02	2.53 to 9.81	5.12	1.91 to 10.91	5.54	2.28 to 10.98	9.11	2.15 to 15.62	6.33	1.05 to 10.28
Dissolved Oxygen	11.28	11.25 to 11.32	11.24	11.20 to 11.28	11.24	11.18 to11.30	11.24	11.20 to 11.26	11.20	11.15 to 11.24
Electrical Conductivity (umhos/cm)	201.1	120.0 to 246.0	293.3	197.0 363.0	586.3	402.0 to 775.0	123.5	44.0 to 183.0	459.0	149.0 to 593.0
Iron	2.36	-0.09 to 8.02	1.05	0.01 to 3.41	-0.26	-0.07 to 1.87	3.18	1.29 to 4.21	0.84	0.60 to 1.01
Magnesium	-0.18	-0.27 to -0.04	-0.20	-0.16 to 0.38	-0.36	-0.48 to -0.19	-0.05	-0.19 to 0.02	-0.14	-0.48 to 0.36
Silicate	1.06	0.75 to 1.46	1.11	0.72 to 1.32	1.15	0.73 to 1.38	1.32	1.02 to 1.65	0.84	0.60 to 1.01
Sodium	70.38	40.79 to 96.97	138.30	75.48 to 266.40	216.14	158.35 to 275.69	69.11	58.29 to 81.92	224.40	222.40 to 225.55
Sulfate	-1.40	-2.95 to -0.44	-1.50	-3.08 to -0.23	-1.40	-3.38 to -0.08	-1.56	-2.15 to -1.23	-1.75	-2.35 to -1.19
Total Hardness ($CaCO_3$)	-13.0	-51.0 to -8.0	-6.0	-28.8 to -0.7	-26.0	-62.5 to -18.9	-1.0	-7.0 to 3.8	-1.5	-4.7 to 0.2
Turbidity (NTU)	10.5	1.1 to 30.9	6.0	-0.3 to 18.9	3.1	0.6 to 9.9	2.9	0.5 to 5.7	2.0	0.4 to 4.5

Unless otherwise stated all values are in mg/L

Figure 10.3.1.1
Specific Weight Losses Versus Time for Copper at Different pH and Hardness Settings

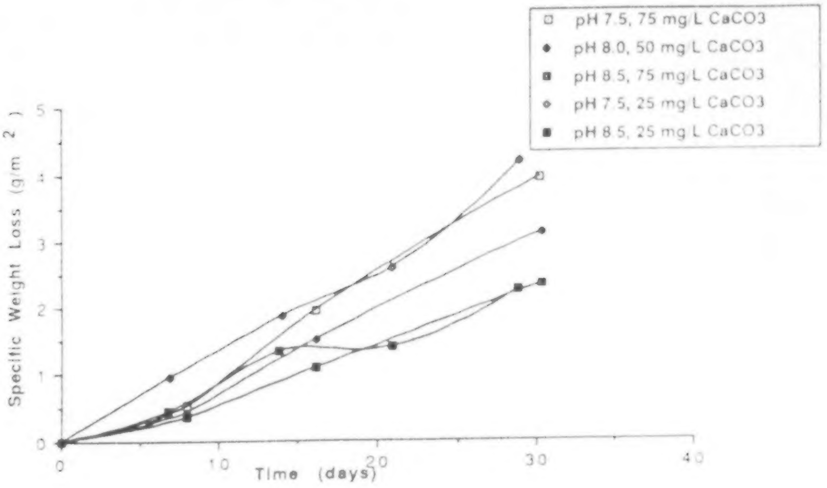
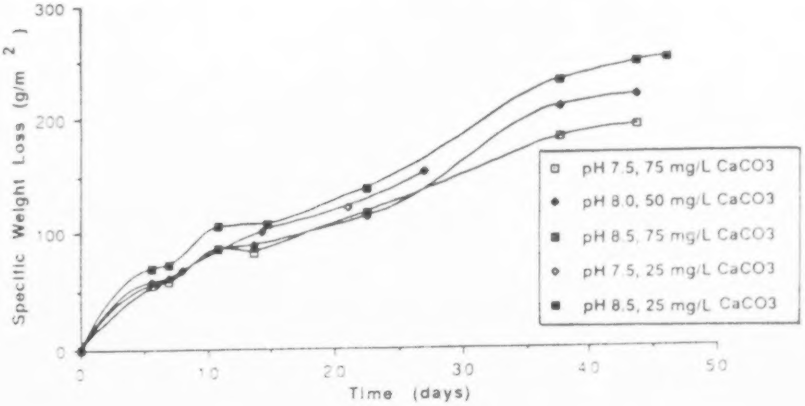


Figure 10.3.2.1
Specific Weight Losses Versus Time for Ductile Iron at Different pH and Hardness Settings



10.4 Statistical Analysis of the Corrosion Rate Data for pH and Hardness Setting.

Tables 10.4.1.1, 10.4.1.2, 10.4.1.3, 10.4.1.4, 10.4.1.5, 10.4.1.6, r10.4.2.1, 10.4.2.2, 10.4.2.3, 10.4.2.4, 10.4.2.5 and 10.4.2.6 provide a summary of the statistical analysis of the corrosion rate data for each pH and hardness setting. Included in each table is the average, standard deviation, range, and calculation of outliers using the Q-test for a 90% probability for each sample set. In addition, the means of each sample set of each setting, were compared using the paired t-test at a 95% probability.

10.4.1 Copper Results

Shown in Figure 10.5.1.6, is that increasing the pH and hardness concentration, although more so from pH increases, caused significant reductions in copper corrosion. The corrosion rate data was significantly different for increasing pH and hardness concentration.

10.4.2 Ductile Iron Results

Unlike the copper results, increasing pH and decreasing hardness concentration caused significant increases in ductile iron corrosion. The corrosion rate data was significantly different for increasing pH and decreasing hardness concentration.

Table 10.4.1.1

Statistical Analysis of the Copper Corrosion Rate Data for pH 8.5 and Total Hardness Concentration 25 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.73	0.065	0.01824	0.052 to 0.078	1 outlier
3	13.81	0.096	0.00318	0.094 to 0.098	1 outlier
2	20.84	0.066	0.00820	0.061 to 0.072	N/A
3	28.88	0.078	0.01302	0.063 to 0.089	N/A

Table 10.4.1.2

Statistical Analysis of the Copper Corrosion Rate Data for pH 7.5 and Total Hardness Concentration 25 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	6.89	0.136	0.00057	0.135 to 0.136	1 outlier
3	13.97	0.133	0.00092	0.132 to 0.133	1 outlier
2	20.94	0.123	0.01174	0.115 to 0.132	N/A
4	29.02	0.145	0.00810	0.137 to 0.155	N/A

Table 10.4.1.3

Statistical Analysis of the Copper Corrosion Rate Data for pH 8.5 and Total Hardness Concentration 75 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	7.96	0.044	0.00389	0.047 to 0.0412	N/A
2	16.13	0.066	0.00078	0.067 to 0.066	N/A
2	30.39	0.077	0.00530	0.081 to 0.073	N/A

Table 10.4.1.4
Statistical Analysis of the Copper Corrosion Rate Data for pH 8.0 and Total Hardness Concentration 50 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
2	7.97	0.054	0.01867	0.067 to 0.041	N/A
2	16.17	0.093	0.00516	0.097 to 0.089	N/A
2	30.36	0.103	0.00177	0.104 to 0.101	N/A

Table 10.4.1.5
Statistical Analysis of the Copper Corrosion Rate Data for pH 7.5 and Total Hardness Concentration 75 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
2	7.98	0.065	0.00212	0.067 to 0.064	N/A
2	16.13	0.120	0.00127	0.121 to 0.120	N/A
2	30.31	0.131	0.00071	0.131 to 0.130	N/A

Table 10.4.1.6
Mean Comparison of the Copper Corrosion Rate Data for the Different pH and Hardness Settings Using the t-Test at a 95% Probability

Time (days)	Comparison of pH and Hardness Settings	
	7.5/75 mg/L to 8.5/75 mg/L	7.5/75 mg/L to 8.0/50 mg/L
8	6.737 > 4.303 Difference is Significant	0.718 > 4.303 Difference is Significant
16	50.030 > 4.303 Difference is Significant	7.123 > 4.303 Difference is Significant
30	14.179 > 4.303 Difference is Significant	6.519 > 4.303 Difference is Significant

Time (days)	Comparison of pH and Hardness Settings
	7.5/25 mg/L to 8.5/25 mg/L
6	6.743 > 2.776 Difference is Significant
14	19.011 > 2.776 Difference is Significant
21	5.642 > 4.303 Difference is Significant
29	6.186 > 4.303 Difference is Significant

Table 10.4.2.1
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH 8.5 and Total Hardness Concentration 25 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation	Range	Outliers
2	8.0	9.01	0.56	9.41 to 8.62	N/A
2	14.10	8.22	0.099	8.29 to 8.15	N/A
2	20.98	6.44	0.064	6.48 to 6.39	N/A
2	27.08	6.06	0.254	6.24 to 5.88	N/A

Table 10.4.2.2
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH 7.5 and Total Hardness Concentration 25 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	8.05	8.40	0.537	8.78 to 8.02	N/A
2	14.17	7.09	0.113	7.17 to 7.01	N/A
2	6.09	9.26	0.863	9.87 to 8.65	N/A
2	20.98	5.82	0.127	5.91 to 5.73	N/A
2	26.97	5.62	0.156	5.73 to 5.51	N/A

Table 10.4.2.3
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH 7.5 and Total Hardness Concentration 75 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	5.64	9.78	0.070	9.85 to 9.71	N/A
3	13.56	6.15	0.095	6.21 to 6.04	N/A
3	22.46	5.22	0.076	5.30 to 5.15	N/A
2	6.93	8.47	0.010	8.47 to 8.46	N/A
2	10.75	8.02	0.226	8.18 to 7.86	N/A
2	37.73	4.80	0.085	4.86 to 4.74	N/A
2	43.84	4.38	0.036	4.40 to 4.35	N/A
2	46.13	4.21	0.022	4.22 to 4.19	N/A

Table 10.4.2.4
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH 8.5 and Total Hardness Concentration 75 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	5.68	12.29	1.067	13.28 to 11.16	N/A
3	14.6	7.31	0.161	7.45 to 7.13	N/A
3	22.51	6.15	0.071	6.23 to 6.09	N/A
2	6.92	10.44	0.056	10.48 to 10.40	N/A
2	10.75	9.84	0.135	9.93 to 9.74	N/A
2	37.72	6.11	0.042	6.14 to 6.08	N/A
2	43.81	5.61	0.014	5.62 to 5.60	N/A
2	46.21	5.42	0.184	5.55 to 5.29	N/A

Table 10.4.2.5
Statistical Analysis of the Ductile Iron Corrosion Rate Data for pH 8.0 and Total Hardness Concentration 50 mg/L as $CaCO_3$

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	5.60	10.39	1.83	11.91 to 8.36	N/A
3	13.55	6.59	0.486	7.13 to 6.18	N/A
3	22.46	5.03	0.206	5.23 to 4.82	N/A
2	6.96	8.78	0.042	8.81 to 8.75	N/A
2	10.76	8.02	0.050	8.05 to 7.98	N/A
2	37.73	5.52	0.022	5.53 to 5.50	N/A
2	43.77	4.97	0.064	5.01 to 4.92	N/A

Table 10.4.2.6
Mean Comparison of the Ductile Iron Corrosion Rate Data for the Different pH and Hardness Settings Using the t-Test at a 95% Probability

Time (days)	Comparison of pH and Hardness Settings 7.5/75 mg/L to 8.5/75 mg/L	 7.5/75 mg/L to 8.0/50 mg/L
6	48.975 > 4.303 Difference is Significant	10.154 > 4.303 Difference is Significant
14	10.748 > 2.776 Difference is Significant	1.539 < 2.776 Difference is not Significant
21	15.488 > 4.303 Difference is Significant	1.499 < 2.776 Difference is not Significant
38	19.540 > 4.303 Difference is Significant	11.597 > 4.303 Difference is Significant
44	45.033 > 4.303 Difference is Significant	11.363 > 4.303 Difference is Significant
46	9.234 > 4.303 Difference is Significant	

Time (days)	Comparison of pH and Hardness Settings 7.5/25 mg/L to 8.5/25 mg/L
8	1.112 < 4.303 Difference is not Significant
14	10.637 > 4.303 Difference is Significant
21	6.165 > 4.303 Difference is Significant
27	2.088 < 4.303 Difference is not Significant

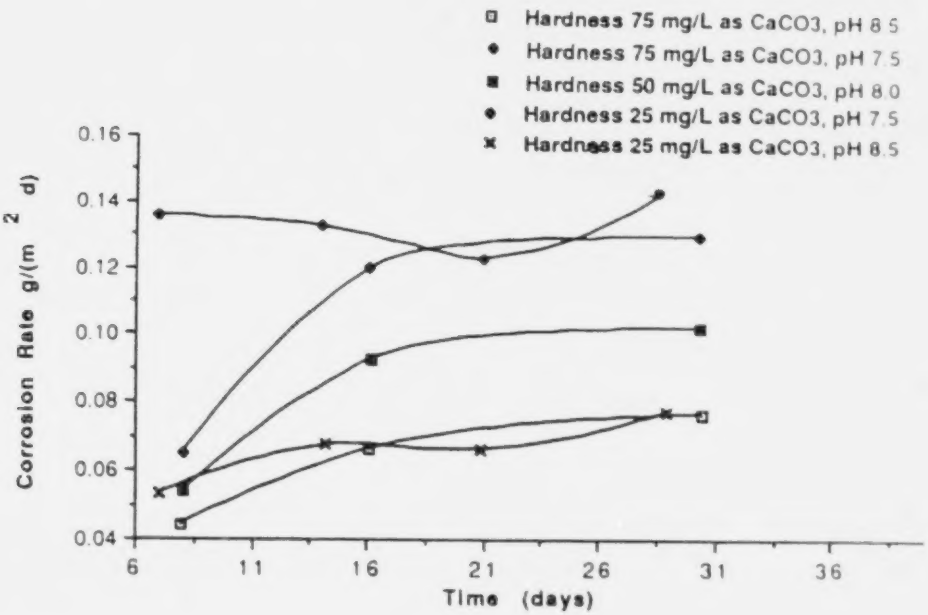
10.5 Corrosion Rates

10.5.1 Copper Experiments

To evaluate the inhibitary performance of the conditioning chemicals: lime, carbon dioxide and sodium hydroxide in reducing copper corrosion at different pH and hardness settings, refer to Figure 10.5.1.1. Figure 10.5.1.1 shows copper corrosion as being pH and alkalinity dependent. Similar to the ductile iron results, is copper corrosion was most greatly influenced by the parameter pH and the associated alkalinity increases. Changing the total hardness concentration from 75 to 25 mg/L as $CaCO_3$, while maintaining either pH settings 7.5 or 8.5, did not significantly reduce the rates of copper corrosion. Regardless of setting, coatings of $CaCO_3$ were not observed to have formed on the surfaces of copper coupons. As well, initial differences in the corrosion rates for some settings may be the contribution of a physical, rather than a chemical factor. Excessive sanding of the surfaces of copper coupons may account for the curves showing corrosion rates increasing with time.

Copper corrosion was significantly reduced with time as a result of pH and alkalinity adjustment. The addition of sodium hydroxide to maintain pH subjected the experimental water to similar water quality changes observed in the pH adjustment` tests. Shown earlier from the results for the pH adjustment chemicals was that by increasing pH, alkalinity and electrical conductivity improved the exposure conditions needed to establish a thick protective film of cuprous oxide to inhibit corrosion. The magnitude of the water quality changes was dependent on the desired pH setting. The subsequent change in water quality in

Figure 10.5.1.1
Corrosion Rates Versus Time for Copper
at Different pH and Hardness Settings



maintaining pH setting 8.5 versus pH 7.5 resulted in a 42% reduction (>3 weeks) in copper corrosion. The pH setting 8.5, regardless of hardness concentration was the most favorable in reducing copper corrosion. Shown in Table 10.5.1.1 are the percent differences in mean corrosion rates of each parameter setting in raltion to the best setting, pH 7.5 and hardness concentration 75 mg/L as $CaCO_3$.

In comparison to the controls, with and without chlorine (Figure 10.5.1.2), the conditioning chemicals were effective at all control parameter settings in reducing copper corrosion. In comparison to the control without chlorine, the following percent reductions in copper corrosion (>25d) were observed;

a. for pH 8.5 hardness concentrations 75 & 25 mg/L as $CaCO_3$ a 53% reduction,

b. for pH 8.0 hardness concentrations 50 mg/L as $CaCO_3$ a 34% reduction; and

c. for pH 7.5 hardness concentrations 75 & 25 mg/L as $CaCO_3$ a 19% reduction.

In comparison to the control with chlorine, the following percent reductions in copper corrosion (>25d) rates were observed:

a. for pH 8.5 and hardness concentrations 75 & 25 mg/L as $CaCO_3$ a 38% reduction,

b. for pH 8.0 hardness concentrations 50 mg/L as $CaCO_3$ a 13% reduction; and

c. for pH 7.5 hardness concentrations 75 & 25 mg/L as $CaCO_3$ no reduction.

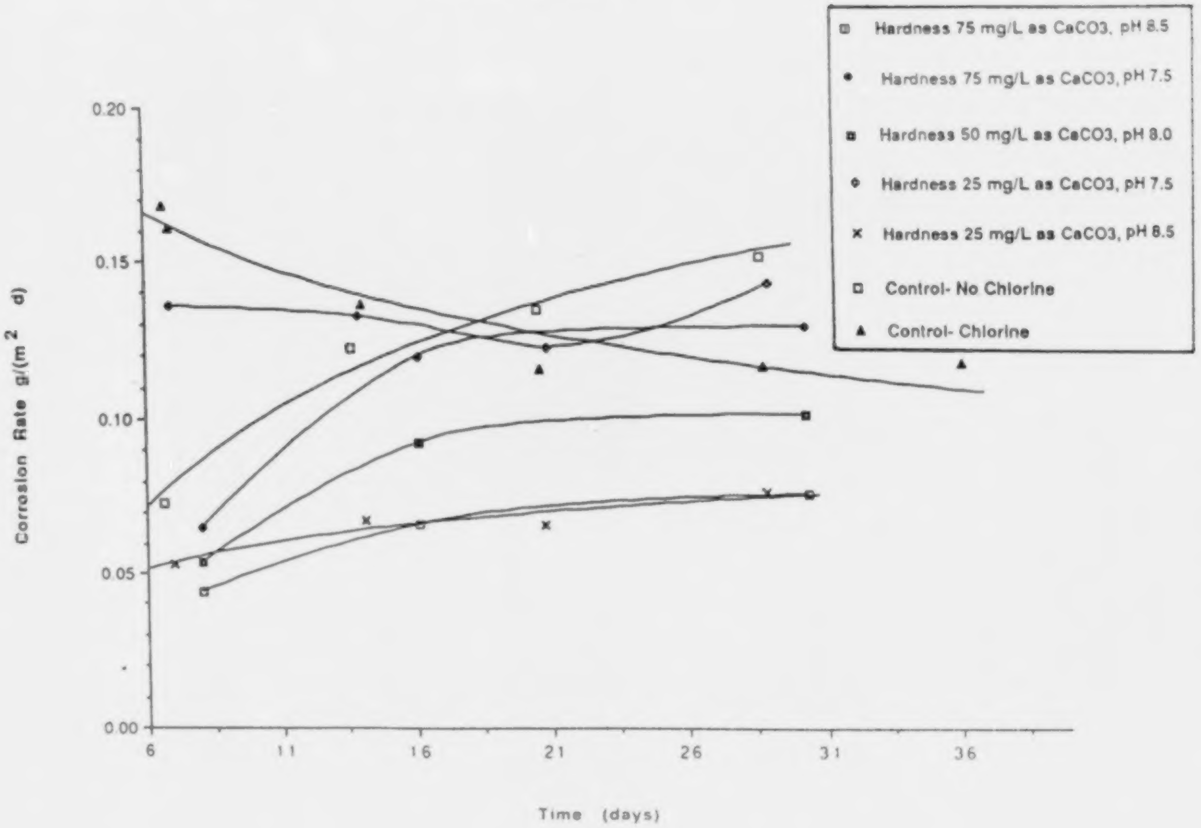
In terms of forecasting in-situ performance of these chemicals, the changes in water quality observed in the laboratory study will not be

Table 10.5.1.1
Percent Differences Between Copper Corrosion Rates of Each Parameter Setting in Relation to the Best Setting: pH 8.5 and Hardness Concentration 75 mg/L CaCO3

Time (days)	Average Percent Difference (%)			
	pH 8.5 & 25 mg/L CaC0$_3$ to pH 8.5 & 75 mg/L CaC0$_3$	pH 7.5 & 25 mg/L CaC0$_3$ to pH 8.5 & 75 mg/L CaC0$_3$	pH 8.0 & 50 mg/L CaC0$_3$ to pH 8.5 & 75 mg/L CaC0$_3$	pH 7.5 & 75 mg/L CaC0$_3$ to pH 8.5 & 75 mg/L CaC0$_3$
7	N/A	N/A	+22.7	+47.7
16	N/A	N/A	+40.9	+81.8
29-30	+1.2	+88.3	+33.8	+70.1

+ = higher
– = lower

Figure 10.5.1.2
Corrosion Rates Versus Time for Copper at Different pH and Hardness Settings Compared to the Controls With and Without Chlorine



comparable to the changes that would result for in-situ application due to the differences in testing methodologies. It is likely, these chemicals for in-situ application will not be as beneficial in reducing copper corrosion as observed in this laboratory study. Determining the magnitude by which these conditioning chemicals will reduce copper corrosion for in-situ performance requires doing a pilot plant study.

10.5.2 Ductile Iron Experiments

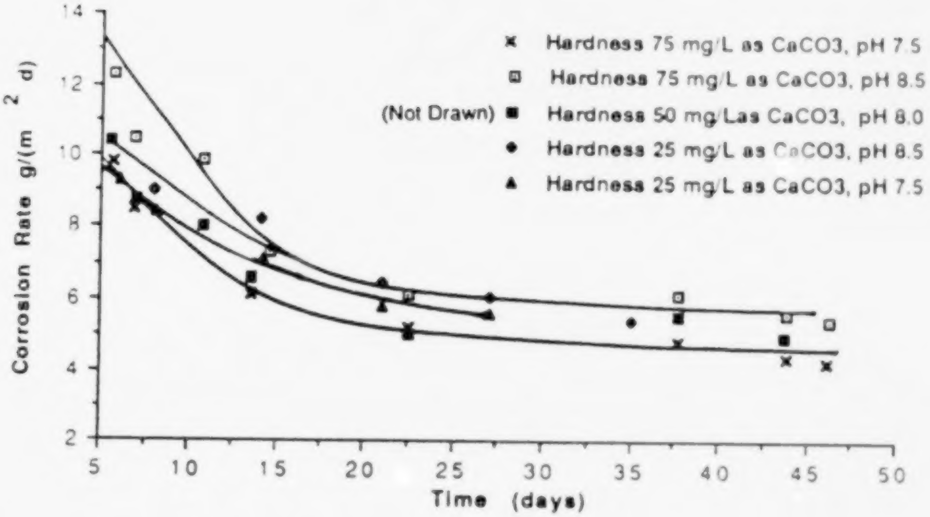
Stabilizing soft, low alkalinity water is a process that is both complex and requires the application of several conditioning chemicals. To stabilize the City's treated water, the conditioning chemicals, lime together with carbon dioxide and sodium hydroxide were applied.

Utilizing batch reactors to evaluate the conditioning chemicals subjected the tests to the same circumstances as previously discussed, whereby the experimental water, in some instances, was substantially changed. These changes in water quality were unavoidable and the result was to cause the precipitation of $CaCO_3$ for some of the control parameter settings, which for in-situ operations might not have occurred. Therefore, the optimum parameter settings which showed the most promise for reducing ductile iron corrosion in the laboratory study may in fact not be the ideal adjustment for the treated water in terms of obtaining the desired performance. The water quality changes associated with the laboratory study and the application of the same control parameter settings to in-situ operations, will cause changes in water quality that are very much different with respect to the changes observed in the laboratory study. At best, interpretation of the results is limited to determining whether lime can effectively reduce ductile iron corrosion when deposited as $CaCO_3$.

According the Caldwell-Lawrence diagram (5 °C and TDS 40 mg/L), the water after the addition of only lime and carbon dioxide showed, for all the desired control parameter settings, the water as either undersaturated or in equilibrium with respect to $CaCO_3$. Yet, precipitation of $CaCO_3$ was observed for all pH settings at total hardness concentrations 50 and 75 mg/L as $CaCO_3$. The precipitation of $CaCO_3$ is attributable to several reasons. The obvious and most important was the increase in alkalinity for the liquid's retention time from sodium hydroxide addition. Increasing the alkalinity of the experimental water served to supersaturate the water with respect to $CaCO_3$. In addition, two other factors may have further contributed to the precipitation of $CaCO_3$. Firstly, is that the presence of scale precipitate in solution may have served to promote heterogeneous nucleation for the spontaneous formation of $CaCO_3$ precipitate. Secondly, is that local increases in pH at the metal's surface caused by corrosion may have promoted the precipitation of $CaCO_3$. Oxygen, in accepting the electrons at the cathode, is reduced and hydroxide formed which locally increases the pH at the metal's surface. Locally, this increase in pH can cause the precipitation of $CaCO_3$, even though the bulk solution is undersaturated. These reactions, however, do not occur for highly undersaturated waters (AWWA, 1985).

To evaluate the inhibitary performance of the conditioning chemicals; lime, carbon dioxide and sodium hydroxide in reducing ductile iron corrosion at different pH and hardness settings, refer to Figure 10.5.2.1. Shown in Figure 10.5.2.1 is ductile iron corrosion as decreasing

Figure 10.5.2.1
Corrosion Rates Versus Time for Ductile Iron
at Different pH and Hardness Settings



with decreasing pH and increasing hardness concentration. Coatings of calcium carbonate were observed to have deposited on the surfaces of ductile iron coupons for all pH settings, at total hardness concentrations 50 and 75 mg/L as $CaCO_3$ (Figures 10.5.2.2, 10.5.2.3, and 10.5.2.4). The difference in performance for the various control parameter settings stems from the changes in water quality for the liquid's weekly retention time. For example, the control parameter setting pH 8.5 and total hardness 75 mg/L as $CaCO_3$ was least effective in reducing ductile iron corrosion, even though a coating of $CaCO_3$ had been deposited on the surfaces of coupons. For this parameter setting, the alkalinity increased initially from 75 mg/L to an average value of 374.3 mg/L as $CaCO_3$ during the liquid's retention time. The hardness concentration decreased daily, by an average of 60% or more. As discussed earlier, having substantially increased alkalinity as was the case for pH settings 8.0 and 8.5, may have intensified the electrochemical process for corrosion. As well, it could have possibly affected the quality of the $CaCO_3$ coating formed. Merrill and Sanks (1978), stated that $CaCO_3$ coatings formed for pH's above 8.0 were less protective than those coatings formed between the pH range 6.8 to 7.3. The pH setting 8.5 was in comparison to the other pH settings, the greatest in terms of being supersaturated with $CaCO_3$. The calcium carbonate precipitation potential average was 26.0 mg/L as $CaCO_3$. This value greatly exceeds Merrill and Sanks (1978) maximum value of 10 mg/L as $CaCO_3$, desired for a water to be protective. Excessive $CaCO_3$ deposition is detrimental to both the pipe's hydraulic capacity and the level of protection offered by the coating. The increase in $CaCO_3$ deposition on the metal's surface may have resulted in too much $CaCO_3$ intermixed with the corrosion scales. According to Stumm (1960) scales with more than 5 to 10% (by weight)

Figure 10.5.2.2
Calcium Carbonate Coatings Formed on Ductile Iron
Coupons for the Setting: pH 7.5 and Hardness Concentration
75 mg/L as $CaCO_3$

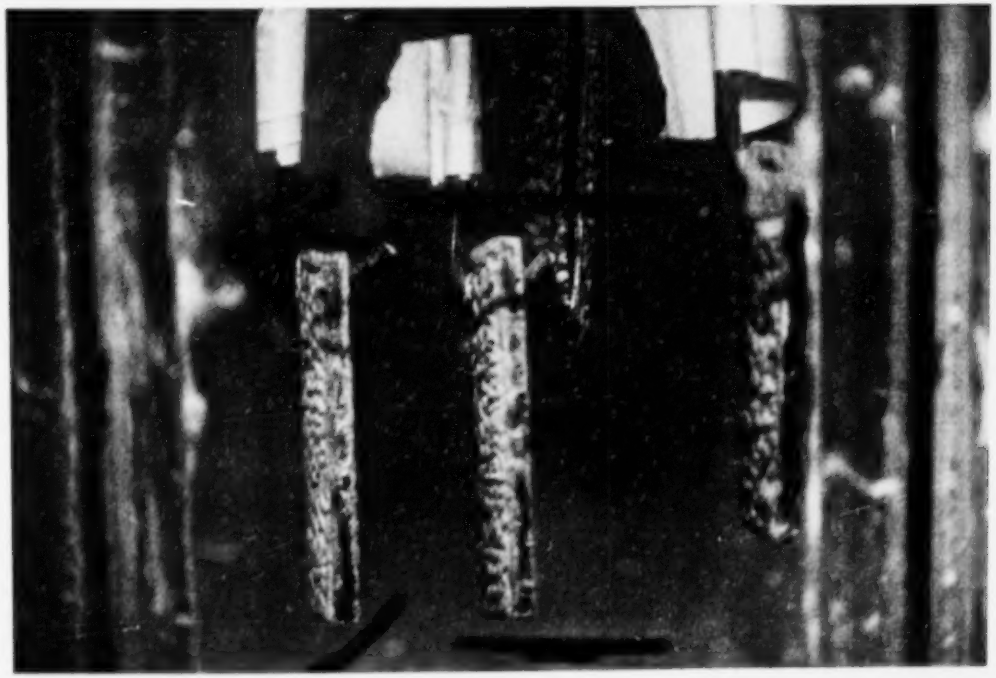


Figure 10.5.2.3
Calcium Carbonate Coatings Formed on Ductile Iron Coupons for the Setting: pH 8.0 and Hardness Concentration 50 mg/L as $CaCO_3$

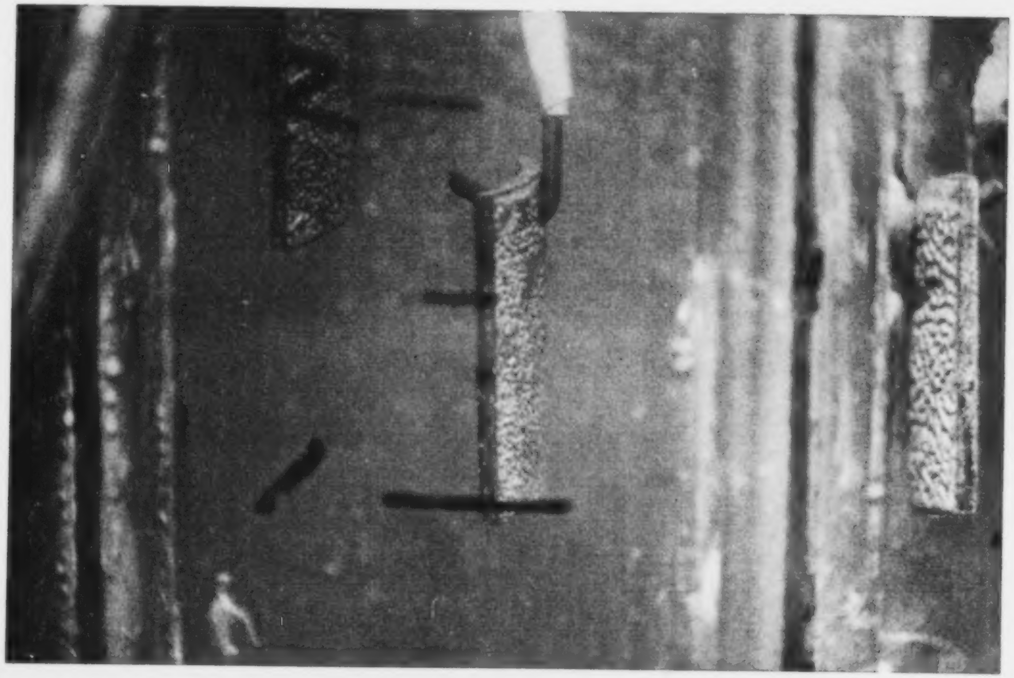
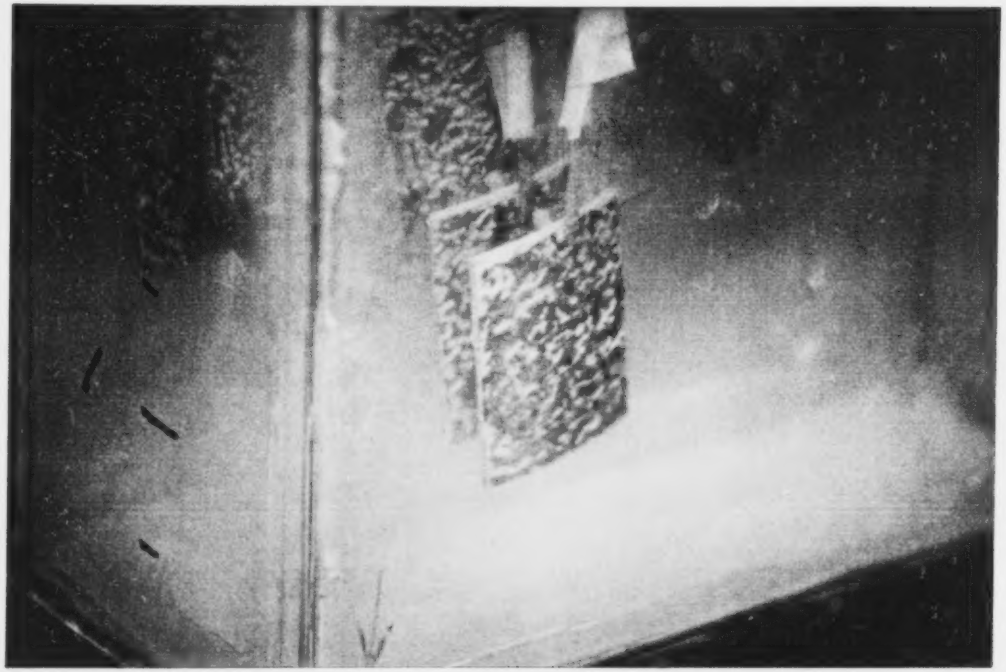


Figure 10.5.2.4
Calcium Carbonate Coatings Formed on Ductile Iron
Coupons for the Setting: pH 8.5 and Hardness Concentration
75 mg/L as $CaCO_3$



$CaCO_3$, were shown to be less protective than those having less. Detailed studies done by the German Gas and Water Association Research Institute, in Karlsruhe (1978), found that high levels of $CaCO_3$ in the protective scale led to a rougher surface layer which was less protective.

Figure 10.5.2.1 shows that the best control parameter setting most favorable in reducing ductile iron corrosion was the setting pH 7.5 and total hardness concentration 75 mg/L as $CaCO_3$. This parameter setting was least affected by adverse changes in water quality to intensify corrosion. The alkalinity for this parameter setting increased initially from 75 mg/L as $CaCO_3$ to an average value of 160 mg/L as $CaCO_3$ for the liquid's weekly retention time. The average calcium carbonate precipitation poptential at this parameter setting was 13.0 mg/L as $CaCO_3$. This calcium carbonate precipitation potential exceeds Merrill and Sanks (1978) recommended maximum 10 mg/L as $CaCO_3$. Although this setting produced the best results, it is not the ideal setting for use in the distribution system. Total hardness concentrations were observed to fluctuate on a daily basis, by an average of 35%. This setting proved best for the laboratory study, in comparison to the other control parameter settings and their resultant water quality changes, mainly, because it best resembled the water quality conditions recommended by Merrill and Sanks (1978) as most favorable for the precipitation of a good protective coating of $CaCO_3$.

In the application of lime, both total hardness and pH were varied over a wide range to determine their influence on inhibitor performance. To determine which control parameters had the greatest influence on corrosion, refer to Figure 10.5.2.1. Analysis shows the control parameter pH as having the greatest influence on corrosion. The significance pH had on increasing corrosion is attributable to the changes in alkalinity, from the addition of sodium hydroxide in maintaining the desired pH settings.

To evaluate how the other parameter settings performed in reducing ductile iron corrosion in comparison to the best setting refer to Table 10.5.2.1. Shown in Table 10.5.2.1 was the next best parameter for reducing ductile iron corrosion was the setting pH 7.5 with a total hardness concentration of 25 mg/L as $CaCO_3$. Calcium carbonate was not observed to have deposited on the surface of coupons at this parameter setting. Analyses of the water shows, that regardless of changes in the amount by which alkalinity or pH increased, the water did not have a sufficient calcium concentration to deposit $CaCO_3$. Results for this setting were similar to the results in testing the pH adjustment chemicals alone, at the same pH setting.

The application of the three conditioning chemicals were, in comparison to the control with chlorine (Figure 10.5.2.4), initially effective in stabilizing the water simulating the treated water. The control parameter setting for best performance was the setting pH 7.5, total hardness 75 mg/L as $CaCO_3$ and a resultant alkalinity of 160 mg/L as $CaCO_3$. This setting, in comparison to the rates of corrosion for the control without chlorine, was not significantly different for the exposure time investigated.

In very low alkalinity, soft waters, small additions of only lime and carbon dioxide may not result in calcium carbonate saturation, if the pH of the water is to be below 8.5 or in the optimum pH range suggested by

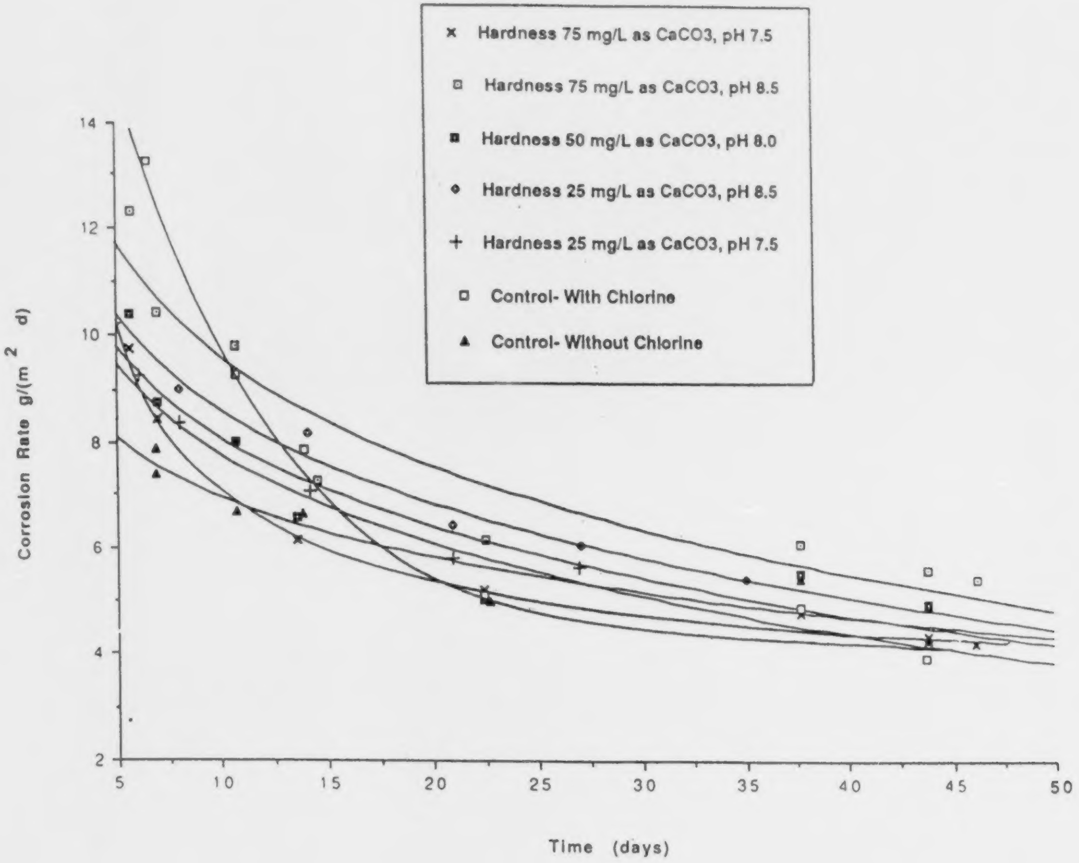
Table 10.5.2.1
Percent Differences Between Ductile Iron Corrosion Rates of Each Parameter Setting in Relation to the Best Setting: pH 7.5 and Hardness Concentration 75 mg/L $CaCO_3$

Time (days)	Average Percent Difference (%)			
	pH 8.5 & 25 mg/L $CaC0_3$ to pH 8.5 & 75 mg/L $CaC0_3$	pH 7.5 & 25 mg/L $CaC0_3$ to pH 7.5 & 75 mg/L $CaC0_3$	pH 8.0 & 50 mg/L $CaC0_3$ to pH 7.5 & 75 mg/L $CaC0_3$	pH 8.5 & 75 mg/L $CaC0_3$ to pH 7.5 & 75 mg/L $CaC0_3$
6	N/A	N/A	+6.2	+25.7
14	N/A	N/A	+7.2	+18.9
21-23	+18.9	+11.5	-3.6	+70.1
37	N/A	N/A	+15.0	+27.3
44	N/A	N/A	+18.1	+28.7

+ = higher
– = lower

Merrill and Sanks (1978). For example, calculation of the Langelier Saturation index (LSI), for changes in water quality from lime and carbon dioxide addition, are shown in Appendix I. The addition of lime and carbon dioxide, to obtain a treated water with a total hardness of 75 mg/L as $CaCO_3$ and a pH of 8.5, provided for a LSI value of -0.05, or slightly undersaturated with $CaCO_3$. However, for a treated water of pH 7.5, the LSI value would be -1.05, or greatly undersaturated with $CaCO_3$. To avoid adding large amounts of lime to supersaturate Yellowknife's raw water with respect to $CaCO_3$ will require, in addition to adding both lime and carbon dioxide, the addition of a pH adjustment chemical to increase only alkalinity. Merrill and Sanks (1978) suggested, for well conditioned water the calcium and alkalinity values should be at least 40 mg/L as $CaCO_3$ and they should be present in equal concentrations. However, analysis of the water to determine $CaCO_3$ saturation for the precipitation potential range of 4 to 10 mg/L as $CaCO_3$, showed the addition of alkalinity alone is needed if the addition of large amounts of lime is to be avoided for a treated water pH of 8.5 or below.

Figure 10.5.2.5
Corrosion Rates Versus Time for Ductile Iron at Different pH and Hardness Settings Compared to the Controls With and Without Chlorine



11.0 Sodium Silicate Results

11.1 Methodology

The sodium silicate inhibitar used for corrosion inhibition of cold water systems with neutral pH, was the Na_2O:SiO_2 ratios of 1:3.22 (type N liquid). The control parameter selected was silicate concentration expressed as SiO_2. For the ductile iron experiments, the average sodium silicate dose concentrations investigated were: 6.9, 10.0, 13.4 and 21.0 mg/L as SiO_2. For the copper experiments, the average dose concentrations investigated were 2.1, 4.0, and 5.9 mg/L as SiO_2. Inability to monitor the silicate concentration on a daily basis made it necessary, for the ductile iron experiments, to change the experimental water approximately every two and half days. For the copper experiments, the water was changed weekly, since it was observed the silicate concentration did not vary with time. When changing the water, both sodium silicate and chlorine were added. A cation sample was immediately taken to determine the initial sodium silicate dose concentration. The water was chlorinated to achieve a total residual concentration, following a 30 minute contact time, of approximately 1.0 mg/L. In addition, for the ductile iron experiments, sodium hydroxide was added to maintain the pH of the water between the range of 7.0 to 7.5. Sample sets were composed of sets of three and were removed weekly.

11.2 Summary of Water Quality Changes

Tables 11.2.1 and 11.2.2 are a summary of the changes in water quality for the sodium silicate tests. The values listed are the average change and the range by which each paramenter changed for the liquid's retention time. For more detailed information refer to Appendix E.

11.3 Specific Weight Loss

11.3.1 Copper Experiments

Figure 11.3.1.1 shows the specific weight losses of copper using sodium silicate at different dose concentrations. Shown was increasing the silicate concentration did not result in a marked change in the weight losses of copper.

11.3.2 Ductile Iron Experiments

Figure 11.3.2.1 shows the specific weight losses of ductile iron using sodium silicate at different dose concentrations. The weight losses are shown increasing with increasing silicate dose concentration.

11.4 Statistical Analysis of the Corrosion Rate Data

Tables 11.4.1.1, 11.4.1.2, 11.4.1.3, 11.4.1.4,11.4.2.1, 11.4.2.2, 11.4.2.3, 11.4.2.4 and 11.4.2.5 provide a summary of the statistical analysis of the corrosion rate data for each silicate dose concentration. Included in each table is the average, standard deviation, range, and calculation of outliers using the Q-test for a 90% probability for each sample set. In addition, the means of each sample set of each dose concentration are compared using the paired t-test at a 95% probability.

Table 11.2.1
Water Quality Summary Sheet for the Copper Experiments of the Sodium Silicate Tests

Parameter	Control Setting					
	2.1 mg/L SiO_2		4.0 mg/L SiO_2		5.9 mg/L SiO_2	
	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	2.9	1.4 to 5.6	4.7	2.4 to 7.7	6.4	3.9 to 10.4
Calcium	0.53	0.49 to 0.56	0.52	0.41 to 0.64	0.48	0.26 to 0.75
Chloride	2.13	1.91 to 2.53	2.16	1.99 to 2.25	2.39	1.77 to 3.55
Copper	1.14	0.74 to 1.36	1.32	0.84 to 1.64	1.11	0.70 to 1.37
Dissolved Oxygen	11.68	11.65 to 11.70	11.67	11.65 to 11.70	11.66	11.62 to 11.70
Electrical conductivity (umhos/cm)	22.0	17.0 to 28.0	24.0	23.0 to 26.0	24.0	20.0 to 29.0
Magnesium	0.13	0.10 to 0.15	0.13	0.09 to 0.17	0.13	0.07 to 0.20
Silicate	0.12	0.04 to 0.20	0.29	0.03 to 0.52	0.32	0.16 to 0.49
Sodium	6.07	5.08 to 6.58	4.73	4.26 to 5.11	5.40	4.46 to 6.99
Sulfate	0.91	0.60 to 1.22	0.92	0.43 to 1.41	1.00	1.00 to 1.12
Total Hardness ($CaCO_3$)	2.1	1.6 to 2.8	1.4	0.8 to 2.2	1.0	0.4 to 2.0
Turbidity (NTU)	0.5	0.4 to 0.6	1.0	0.7 to 1.3	0.6	0.5 to 1.0

Unless otherwise stated all values are in mg/L

Table 11.2.2
Water Quality Summary Sheet for the Ductile Iron Experiments of the Sodium Silicate Tests

Parameter	Control Setting							
	6.85 mg/L SiO_2		10.0 mg/L SiO_2		13.4 mg/L SiO_2		21.0 mg/L SiO_2	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
Alkalinity ($CaCO_3$)	59.0	41.8 to 80.3	52.5	43.4 to 63.4	56.7	42.1 to 71.9	54.4	38.6 to 84.6
Calcium	-0.12	-0.69 to 0.41	0.06	-0.53 to 0.78	-0.29	-1.38 to 0.63	-0.20	-1.14 to 0.60
Chloride	2.26	-0.65 to 5.14	2.56	-0.11 to 5.49	2.19	-1.40 to 7.50	2.24	-0.04 to 5.83
Dissolved Oxygen	11.25	11.20 to 11.33	11.26	11.15 to 11.36	11.26	11.18 to 11.37	11.28	11.25 to 11.35
Electrical conductivity (umhos/cm)	71.7	40.0 to 95.0	69.3	61.o to 86.0	77.0	52.0 to 91.0	73.4	61.0 to 111.0
Magnesium	-0.03	-0.18 to 0.07	0.04	-0.17 to 0.10	-0.03	-0.12 to 0.06	-0.04	-0.11 to 0.11
Silicate	-0.79	-1.46 to -0.37	-1.54	-2.35 to -1.10	-2.11	-2.88 to -1.29	-3.76	-4.63 to -2.60
Sodium	25.99	20.26 to 35.16	23.44	18.12 to 29.47	25.03	18.34 to 30.59	22.15	16.63 to 33.69
Sulfate	-1.32	-2.27 to -0.35	-1.42	-2.58 to 0.60	-1.22	-2.58 to -0.11	-1.00	-2.58 to -0.11
Total Hardness ($CaCO_3$)	-0.7	-2.0 to 0.5	0.2	-1.0 to 2.0	-0.2	-1.0 to 1.2	0.8	-2.8 to 1.4
Turbidity (NTU)	11.0	0.2 to 25.6	12.3	1.8 to 27.6	10.1	0.8 to 28.6	10.3	0.4 to 35.6

Unless otherwise stated all values are in mg/L

Figure 11.3.1.1
Specific Weight Losses Versus Time for Copper Using Sodium Silicate at Different Concentrations

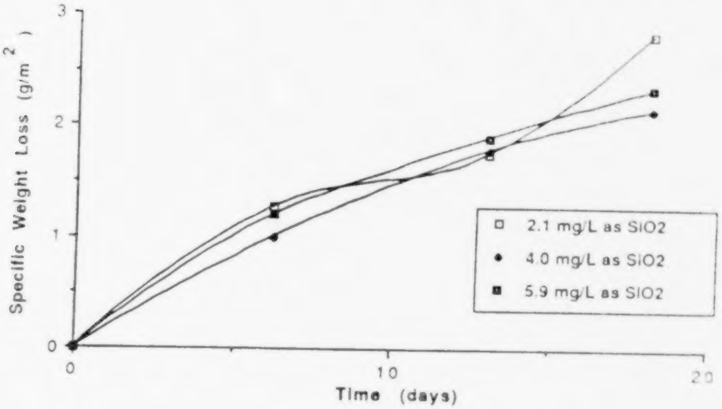


Figure 11.3.2.1
Specific Weight Losses Versus Time for Ductile Iron Using Sodium Silicate at Different Concentrations

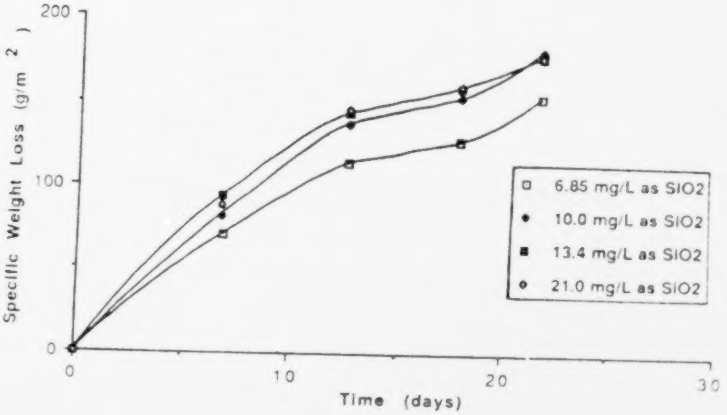


Table 11.4.1.1
Statistical Analysis of the Copper Corrosion Rate Data for the Silicate Concentration 2.1 mg/L as SiO_2

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	6.23	0.204	0.00694	0.211 to 0.197	N/A
3	13.01	0.134	0.00866	0.146 to 0.125	N/A
3	18.21	0.156	0.0052	0.173 - 0.153	1 Outlier

Table 11.4.1.2
Statistical Analysis of the Copper Corrosion Rate Data for the Silicate Concentration 4.0 mg/L as SiO_2

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	6.23	0.160	0.00916	0.170 to 0.153	N/A
3	13.01	0.137	0.00622	0.141 to 0.133	1 Outlier
3	18.21	0.119	0.00156	0.120 to 0.118	1 Outlier

Table 11.4.1.3
Statistical Analysis of the Copper Corrosion Rate Data for the Silicate Concentration 5.9 mg/L as SiO_2

No. of Coupons	Detention Time (days)	Average $g/(m^2\ d)$	Standard Deviation $g/(m^2\ d)$	Range $g/(m^2\ d)$	Outliers
3	6.23	0.193	0.01715	0.212 to 0.178	N/A
3	13.01	0.146	0.00283	0.148 to 0.144	1 Outlier
3	18.21	0.129	0.00172	0.130 to 0.127	N/A

Table 11.4.1.4
Mean Comparison of the Copper Corrosion Rate Data for the Different Silicate Concentrations Using the t-Test at a 95% Probability

Time	Comparison of Silicate Concentrations		
(days)	2.1 to 4.0 mg/L	2.1 to 5.9 mg/L	4.0 to 5.9 mg/L
6	6.630 > 2.776 Difference is Significant	1.025 < 2.776 Difference is Not Significant	2.927 > 2.776 Difference is Significant
13	0.414 < 2.776 Difference is Not Significant	1.811 < 2.776 Difference is Not Significant	1.863 < 2.776 Difference is Not Significant
18	9.638 > 2.776 Difference is Significant	8.924 > 2.776 Difference is Significant	6.515 > 2.776 Difference is Significant

Table 11.4.2.1
Statistical Analysis of the Ductile Iron Corrosion Rate Data for the Silicate Concentration 6.9 mg/L as SiO_2

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.79	10.33	0.417	10.62 to 10.03	N/A
2	12.64	8.94	0.191	9.07 to 8.80	N/A
2	17.85	7.07	0.347	7.31 to 6.82	N/A
2	21.67	7.07	0.022	7.09 to 7.06	N/A

Table 11.4.2.2
Statistical Analysis of the Ductile Iron Corrosion Rate Data for the Silicate Concentration 10.0 mg/L as SiO_2

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.72	12.14	0.834	12.73 to 11.55	N/A
2	12.64	10.82	0.672	11.29 to 10.34	N/A
2	17.85	8.56	0.431	8.86 to 8.25	N/A
2	21.67	8.32	0.092	8.38 to 8.25	N/A

Table 11.4.2.3
Statistical Analysis of the Ductile Iron Corrosion Rate Data for the Silicate Concentration 13.4 mg/L as SiO_2

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.79	13.81	0.054	13.83 to 13.76	N/A
2	12.64	11.30	0.545	11.68 to 10.91	N/A
2	17.85	8.89	0.149	8.99 to 8.78	N/A
2	21.67	8.18	0.240	8.35 to 8.01	N/A

Table 11.4.2.4
Statistical Analysis of the Ductile Iron Corrosion Rate Data for the Silicate Concentration 21.0 mg/L as SiO_2

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.79	13.09	0.785	13.64 to 12.53	N/A
2	12.64	11.45	0.269	11.64 to 11.26	N/A
2	17.85	8.91	0.057	8.95 to 8.87	N/A
2	21.67	8.15	0.297	8.36 to 7.94	N/A

Table 11.4.2.5
Mean Comparison of the Ductile Iron Corrosion Rate Data for the Different Silicate Concentrations Using the t-Test at a 95% Probability

Time	Comparison of Silicate Concentrations	
(days)	6.85 mg/L to 10.0 mg/L	10.0 mg/L to 13.4 mg/L
7	1.574 < 4.303 Difference is Not Significant	2.826 < 4.303 Difference is Not Significant
13	3.805 < 4.303 Difference is Not Significant	0.785 < 4.303 Difference is Not Significant
18	3.808 < 4.303 Difference is Not Significant	0.069 < 4.303 Difference is Not Significant
22	18.688 > 4.303 Difference is Significant	0.770 < 4.303 Difference is Not Significant

Time	Comparison of Silicate Concentrations	
(days)	6.85 mg/L to 13.4 mg/L	10.0 mg/L to 21.0 mg/L
7	11.700 > 4.303 Difference is Significant	1.173 < 4.303 Difference is Not Significant
13	5.779 > 4.303 Difference is Significant	1.231 < 4.303 Difference is Not Significant
18	6.816 > 4.303 Difference is Significant	1.138 < 4.303 Difference is Not Significant
22	6.513 > 4.303 Difference is Significant	0.773 < 4.303 Difference is Not Significant

Time	Comparison of Silicate Concentrations	
(days)	6.85 mg/L to 21.0 mg/L	13.4 mg/L to 21.0 mg/L
7	3.791 < 4.303 Difference is Not Significant	1.294 < 4.303 Difference is Not Significant
13	10.759 > 4.303 Difference is Significant	0.349 < 4.303 Difference is Not Significant
18	7.400 > 4.303 Difference is Significant	0.177 < 4.303 Difference is Not Significant
22	5.129 > 4.303 Difference is Significant	0.111 < 4.303 Difference is Not Significant

11.4.1 Copper Results

Comparison of the mean of the dosage concentration 6.85 mg/L to the means of the dosages 13.4 mg/L and 21.0 mg/L as SiO_2 were, for most sampling dates, significantly different at a 95% confidence level. However, mean comparison between the dosages 10.0 mg/L, 13.4 mg/L and 21.0 mg/L were, for most sampling dates, not significantly different. Small sample sets, and their associated variance, made it difficult to statistically show there being a difference between settings. The data tendency, however, shows copper corrosion as decreasing with increasing silicate dose concentration.

11.4.2 Ductile Iron Results

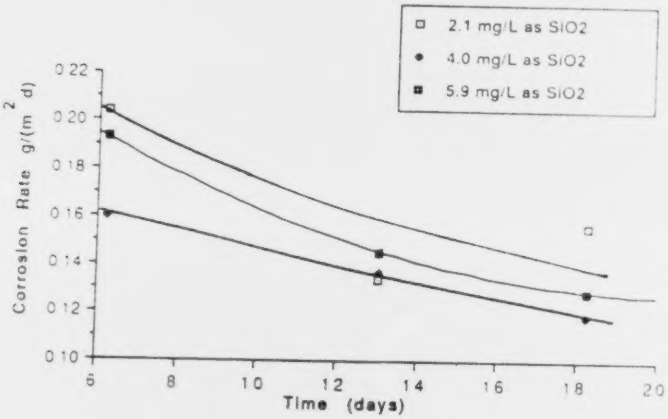
Mean comparison between settings were, for some sampling dates, significantly different at a 95% confidence level. Sodium silicate, for the dosages investigated, was not effective in reducing ductile iron corrosion. Instead, it was observed that by increasing the silicate dosage concentration, ductile iron corrosion increased. In addition, the data suggests there is only small differences between corrosion rates above the dose concentration of 10 mg/L as SiO_2.

11.5 Corrosion Rates

11.5.1 Copper Experiments

To evaluate the inhibitory performance of sodium silicate on copper corrosion at different silicate dose concentrations, refer to Figure 11.5.1.1. Previous studies have shown that silicate is not deposited on copper and that this is due to the metal's inability to produce the required

Figure 11.5.1.1
Copper Corrosion Rates Versus Time at Different Silicate Concentrations



type of corrosion scale needed to deposit a silicate gel. Instead, sodium silicate's ability to reduce copper corrosion is attributed to the resultant increases in pH and total alkalinity as a result of chemical addition. The amount by which the pH and total alkalinity is increased is dependent on the silicate dosage. The higher the silicate dosage, the greater the fraction of total alkalinity that is due to the silicate system. Shown in Figure 11.5.1.1, was that copper corrosion decreased slightly for higher silicate dosages. However, unexpectly the maximum 5.9 mg/L silicate dose concentration was not the best setting. Instead, the average silicate concentration of 4.0 mg/L as SiO_2 gave the best results. Shown in Table 11.5.1.1 are the percent differences between mean corrosion rates of each silicate concentration in relation to the best setting, 4.0 mg/L as SiO_2.

The changes to pH and total alkalinity as a result of silicate addition, were small. This suggests that if there is to be a significant reduction in copper corrosion, higher silicate dosages are needed. The pH of the raw water increased by only 4 percent (7.07 to 7.32) for the silicate dosage of 5.9 mg/L as SiO_2. As well, the total alkalinity of the raw water increased from 18.3 mg/L to 20.0 mg/L as $CaCO_3$, for the silicate dosage of 5.9 mg/L as SiO_2. The changes to pH and total alkalinity were not enough for there to be a significant reduction in copper corrosion at the silicate dose concentrations investigated.

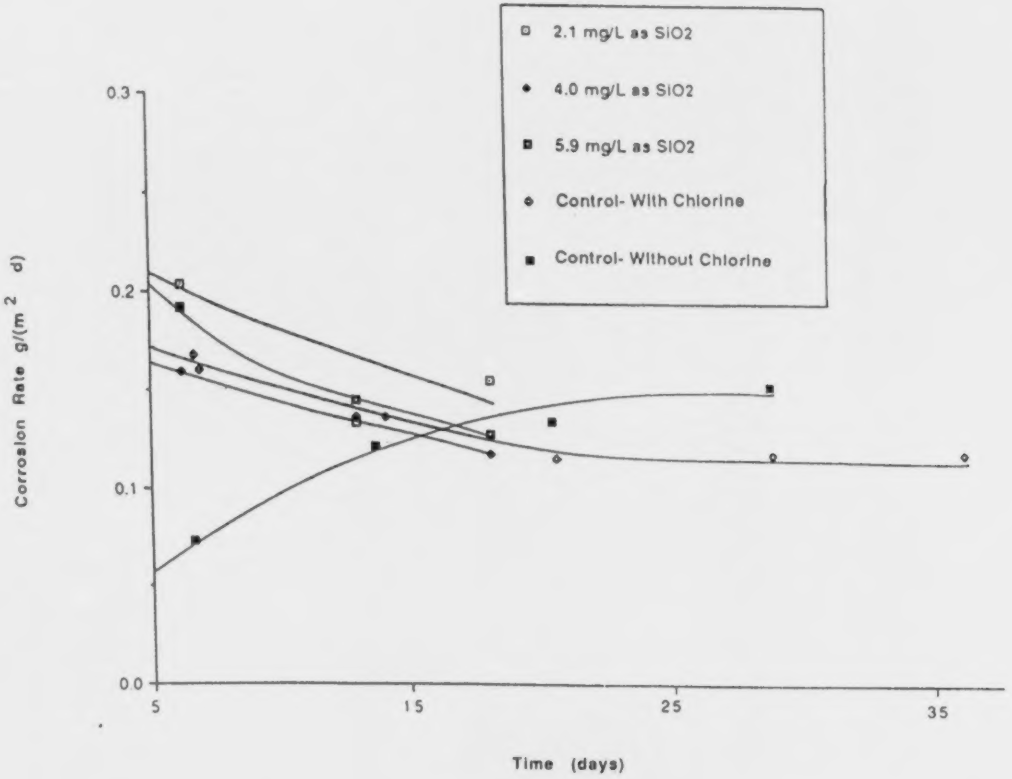
To evaluate the performance of sodium silicate in reducing copper corrosion, in comparison to the controls with and without chlorine, refer to Figure 11.5.1.2. Shown in Figure 11.5.1.2 is there is little difference between the corrosion rates for the silicate dose concentrations compared to the control with chlorine. The comparison suggests higher silicate dose

Table 11.5.1.1
Percent Differences Between Copper Corrosion Rates of Each Parameter Setting in Relation to the Best Setting: 4.0 mg/L as SiO_2

Time (days)	Average Percent Difference (%)	
	2.1 mg/L to 4.0 mg/L as SiO_2	5.9 mg/L to 4.0 mg/L as SiO_2
6	+27.5	+20.6
13	-2.2	+6.6
18	+31.1	+8.4

+ = higher
− = lower

Figure 11.5.1.2
Corrosion Rates Versus Time for Copper at Different Silicate Concentrations Compared to the Controls With and Without Chlorine



concentrations than those considered will have to be investigated if sodium silicate is to be shown beneficial in reducing copper corrosion.

11.5.2 Ductile Iron Experiments

To evaluate the inhibitory performance of sodium silicate on ductile iron corrosion at different silicate dose concentrations, refer to Figure 11.5.2.1. Shown in Figure 11.5.2.1 is ductile iron corrosion as having increased with increasing silicate dosage. The silicate dosage shown most promising in reducing ductile iron corrosion, was the average dose concentration of 6.9 mg/L as SiO_2. In addition, shown is the performance of the other average silicate dose concentrations, 10.0, 13.4 and 21.0, as being similar at a 95% confidence level. The corrosion rates at these silicate dose concentrations were, after a 20 day exposure time, 13 percent higher than that of the rate for the 6.9 mg/L silicate dosage. This indicates the application of silicate, for dosages above the concentration of 10 mg/L as SiO_2, is not beneficial for reducing ductile iron corrosion for the exposure time investigated. Not known however, is if lower dose concentrations than those investigated would be as good, better, or worse. Shown in Table 11.5.2.1 are the percent differences between mean corrosion rates of each silicate concentration in relation to the best setting, 6.9 mg/L as SiO_2.

Sodium hydroxide was added periodically to maintain the pH of the experimental water within the pH range 7.0 to 7.5. Because the experimental waters were changed every two and half days, the changes in water quality from the addition of sodium hydroxide were not considered to have greatly influenced corrosion.

Figure 11.5.2.1
Ductile Iron Corrosion Rates Versus Time at Different Silicate Concentrations

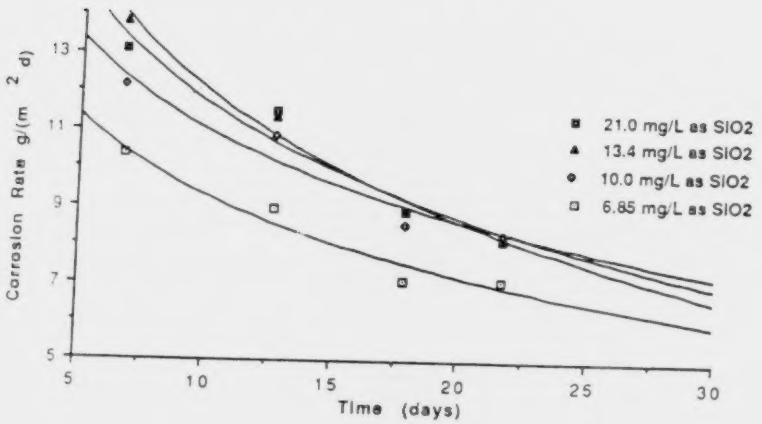


Table 11.5.2.1
Percent Differences Between Ductile Iron Corrosion Rates of Each Parameter Setting in Relation to the Best Setting: 6.9 mg/L as SiO_2

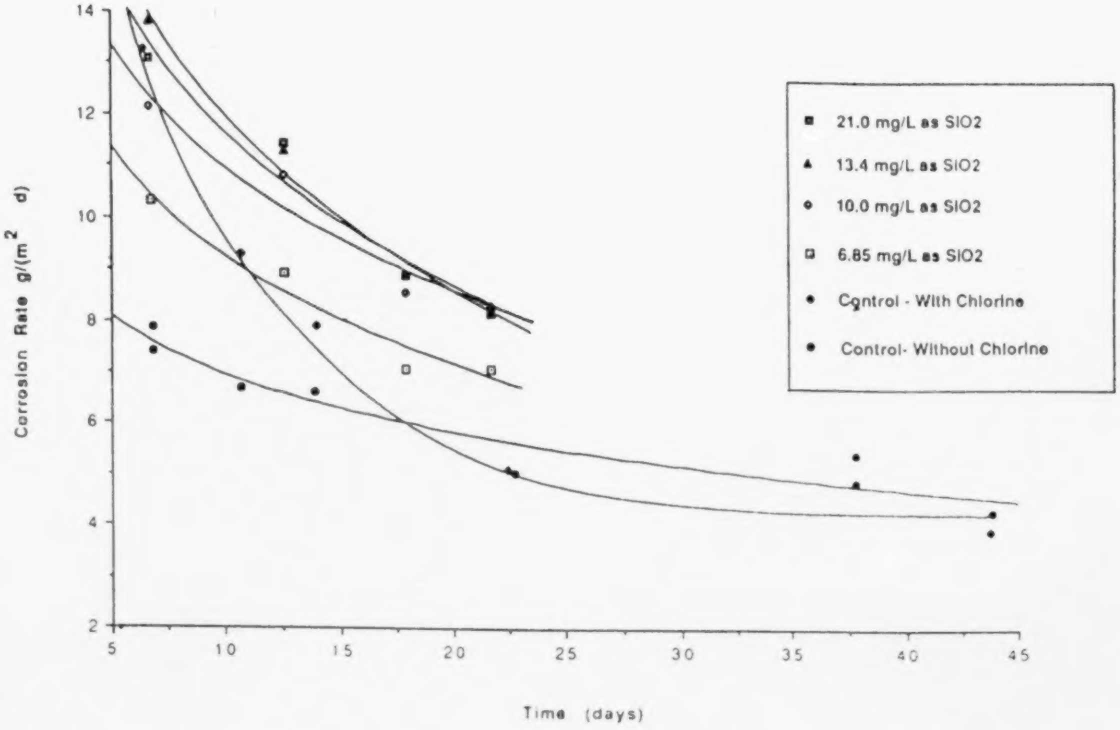
Time (days)	Average Percent Difference (%)		
	2.1 mg/L to 4.0 mg/L as SiO_2	5.9 mg/L to 4.0 mg/L as SiO_2	21.6 mg/L to 6.85 mg/L as SiO_2
6	+17.5	+33.7	+26.7
13	+21.0	+26.4	+28.1
18	+21.1	+25.7	+26.0
22	+17.7	+15.7	+15.3

+ = higher
− = lower

To evaluate the performance of sodium silicate in reducing ductile iron corrosion, in comparison to the controls with and without chlorine, refer to Figure 11.5.2.2. Shown in Figure 11.5.2.2 is sodium silicate, above the average dose concentration 10.0 mg/L as SiO_2, was simply not effective in reducing the ductile iron corrosion for the exposure time investigated. Figure 11.5.2.2 shows the silicate dose concentrations 10.0 mg/L as SiO_2 and higher as having increased the corrosion rates in comparison to the control with chlorine. The corrosion rates for the silicate dosages above 10 mg/L as SiO_2 were 38% higher than the control with chlorine, for a 20 day exposure time.

Similar to polyphosphate, sodium silicate at high dose concentrations has a softening effect on corrosion scales to reduce the level of protection offered by protective scales. The silicate dose concentration of 6.9 mg/L as SiO_2, in comparison to the control with chlorine, was only initially effective in reducing corrosion. Silicate for the dose concentrations investigated was not shown to be beneficial as an inhibitor for ductile iron corrosion, although this may be attributable to the inhibitor's slow film formation. The interaction of silicate with corrosion scales, to establish a protective film, is slow, with some estimating as long as a month for film development (AWWA, 1985). Consequently, the exposure time for testing sodium silicate may have been insufficient for effective film development for the conditions under which the tests were performed. If silicate is to be shown effective in reducing ductile iron corrosion, then additional testing is required and that testing must be for a greater length of time.

Figure 11.5.2.2
Corrosion Rates Versus Time for Ductile Iron at Different Silicate Concentrations Compared to the Controls With and Without Chlorine



12.0 Microbiology Results

12.1 Objective

Microbial research was conducted to determine the types and concentrations of bacterial species in Yellowknife's untreated and treated waters, as well as in corrrosion scales removed from distribution piping.

12.2 Methodology

Both laboratory samples and water samples collected from the community were analyzed for corrosion-causing and corrosion-intensifying bacteria. The following types of waters tested were:

1.) Yellowknife's treated water collected from the Professional Building located on Franklin Avenue, in the offices of the Mackenzie Regional Health Services.

2.) Yellowknife's untreated water collected from the raw water supply line prior to treatment at Pumphouse No. 1.

3.) The experimental raw water used in Phase 2.

4.) The experimental water used in Phase 2 but treated with chlorine and different concentrations of polyphosphate. This water was exposed to copper and ductile iron coupons and tested for its microbial flora.

In addition, a section of ductile iron pipe removed from Pumphouse No. 1 was sampled for its corrosion scales and was tested for its microbial flora.

Each water sample was examined for the following different species of bacteria:

i.) heterotrophic iron-reducing bacteria;

ii.) sulfate-reducing bacteria;

iii.) iron-oxidizing bacteria; and

iv.) sulfur-oxidizing bacteria.

The experimental waters and the corrosion scales were also examined for total and fecal coliforms and fecal Streptococcus.

The following methods were used: aerobic and anaerobic heterotrophic plate counts were performed according to section 9215 of Standard Methods (AWWA-AHPA-WPCF, 1989). Coliforms were enumerated according to section 9222A and 9222D of Standard Methods (AWWA-AHPA-WPCF, 1989). Fecal Streptococci were enumerated according to section 9230C of Standard Methods (AWWA-AHPA-WPCF, 1989). Iron-reducing bacteria (Figure 12.2.1) were enumerated by the 5-tube MPN method, using dilutions of 1.0 to 0.0001 mL in the media B_{10} Broth (1, Appendix J). According to section 9240 of Standard Methods (AWWA-AHPA-WPCF, 1989) iron oxidizing bacteria are commonly reported as either present or absent by direct microscopic examination of the water. However, this technique was not feasible, given the visual acceptability of Yellowknife's River water. Instead, enrichment cultures using Winogradsky's medium (Figure 12.2.2) for iron bacteria were established (3, Appendix J). These cultures were examined for visual evidence of iron oxidation. The enrichments were then examined microscopically for identification of the types of iron bacteria present.

Figure 12.2.1
Iron-reducing Bacteria
Right - Uninoculated Control
Left - Inoculated: Yellowknife River Water

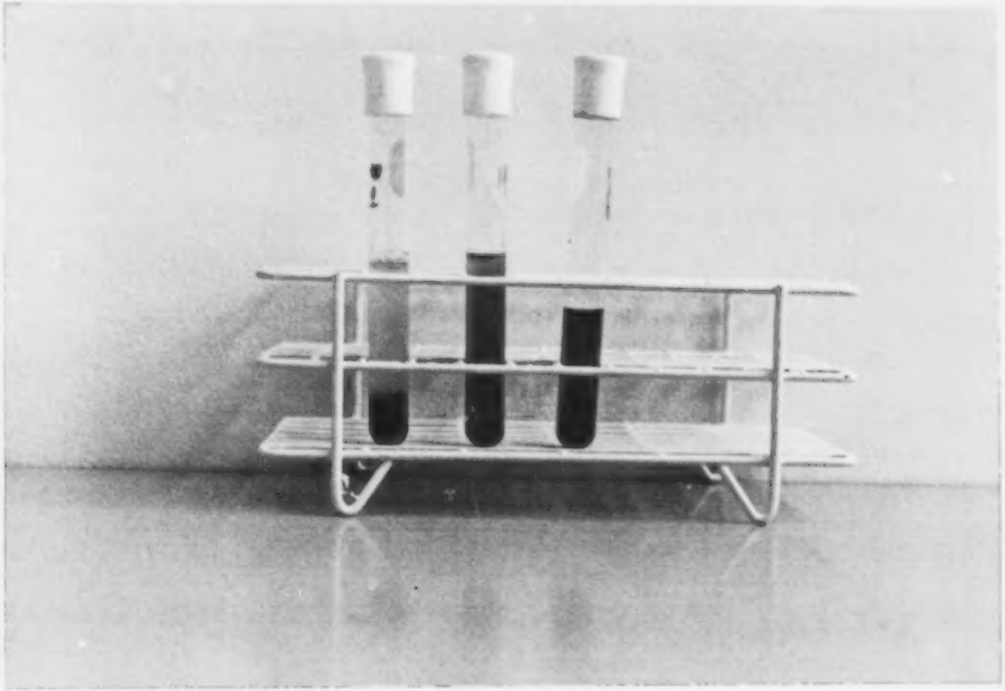
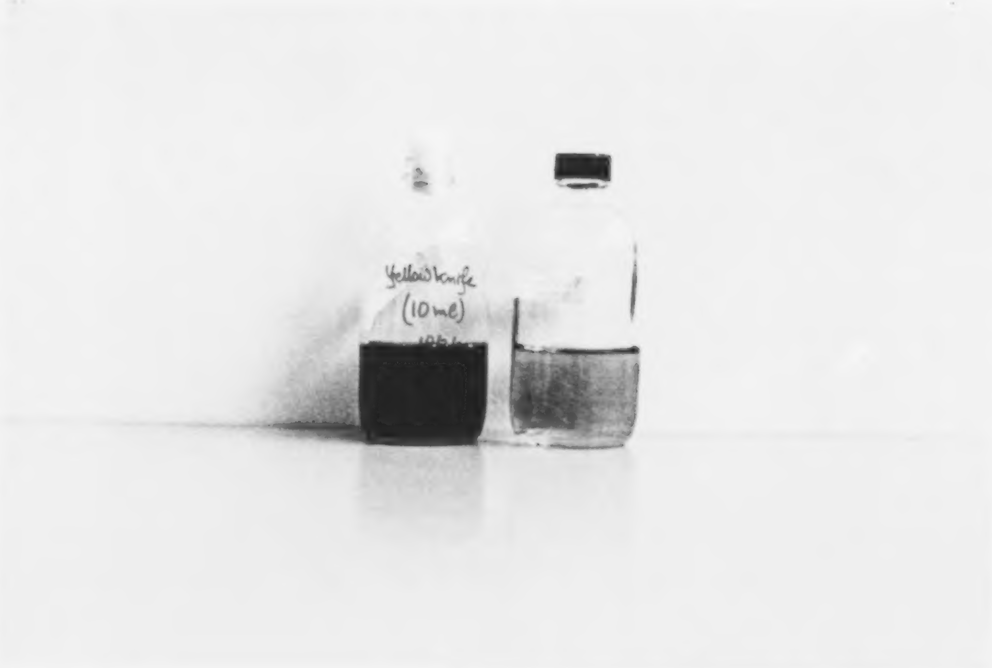


Figure 12.2.2
Iron-oxidizing Bacteria
Right - Uninoculated Control
Left - Inoculated: Yellowknife River Water


Yellowknife
(10 ml)

Sulfate reducers (Figure 12.2.3) were enumerated using Butlin's medium (2, Appendix J). Sulfate-reduction in the Butlin's medium was monitored for the formation of FeS, which is a black precipitate. Sulfur-oxidizing bacteria were enriched using Starkey's medium (3, Appendix J) and monitored for changes in pH. Cultures showing a drop in pH were examined microscopically. Uninoculated, negative controls were used for all tests.

Water samples treated with chlorine and polyphosphate were collected, following a seven day exposure time with the metals ductile iron and copper immersed, and examined for the different microorganisms using the above methods. Ductile iron coupons, showing visible scale, were aseptically washed in 30 mL of sterile water to remove scale deposits. The wash water was then diluted to 50 mL and used for inoculation.

12.3 Results of the Microbial Research

Microbiological analysis of the untreated supply water, collected from Pumphouse No. 1, indicates the presence of low concentrations of corrosion-causing and corrosion-intensifying bacteria. Corrosion-causing microorganisms include heterotrophic iron, sulfate, sulfite, and thiosulfate reducing bacteria. Corrosion-intensifying bacteria include iron and sulfur oxidizing bacteria. The bacteria most prevalent in the untreated water were the species thiosulfate and heterotrophic iron reducing bacteria.

Figure 12.2.3
Sulfate-reducing Bacteria
Right - Uninoculated Control
Left - Inoculated: Yellowknife River Water

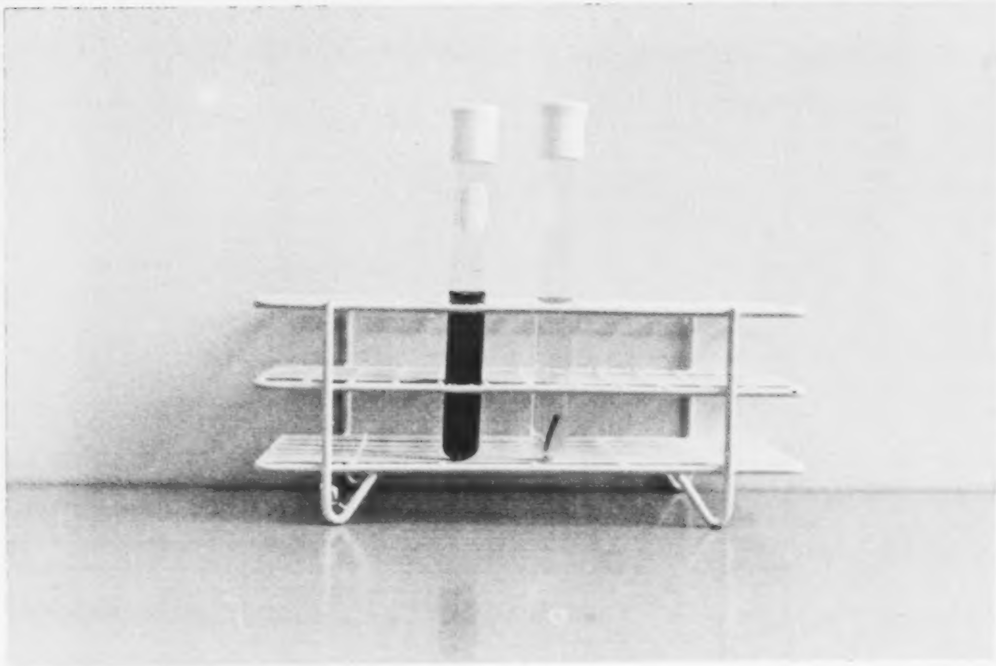


Table 12.3.1 summarizes the microbial flora for the untreated water sample collected from Pumphouse No. 1. The microflora results of the untreated water sample may, in reality, be higher than if the sample had been collected directly from the Yellowknife River. This is because the sample had been exposed to a portion of the distribution system prior to sampling. That portion of the distribution system was the submarine supply pipeline. The pipeline is a partly lined steel pipe with an epoxy inside lining and is approximately 8.5 km long. The epoxy lining, however, has been burnt-off at the weld joints. The water, in travelling through this pipeline may have been contaminated by its biofilm, increasing the bacteria numbers observed.

Although the bacterial populations in the untreated water are low, there is present a variety of bacteria capable of causing or intensifying corrosion. Depending on the effectiveness of Yellowknife's chlorination program, it is possible for these microorganisms to proliferate and eventually cause both water quality and corrosion problems.

Table 12.3.1 summarizes the microbial flora for the treated water sample collected from a distribution tap in the offices of the Mackenzie Regional Health Services building. Microbiological analysis of the treated water shows an absence of many of the bacteria species identified in the untreated water. Only for the thiosulfate reducing bacteria, is regrowth shown as occurring. Their presence after 48 hours, is the regrowth of bacteria injured in the disinfection process. Chlorination is responsible in having eliminated most of the bacterial species for the location sampled.

Table 12.3.1
Microflora for Yellowknife's Raw and Treated Supply Water
(March 16, 1990)

MPN (organism/mL)	Raw Water	Treated Water
Heterotrophic iron reducers (20 °C)		
48hr	9.3	<0.3
7d	23	<0.3
14d	93	<0.3
21d	93	<0.3
Sulfate-reducers (20 °C)		
48hr	<0.3	<0.3
7d	<0.3	<0.3
14d	0.9	<0.3
21d	1.5	<0.3
H_2S produced	yes	no
Sulfite-reducers (20 °C)		
48hr	0.4	<0.3
7d	4	<0.3
14d	4	<0.3
21d	4	<0.3
H_2S produced	yes	no
Thiosulfate-reducers (20 °C)		
48hr	9.3	<0.3
7d	23	<0.3
14d	240	<0.3
21d	240	9.3
H_2S produced	yes	yes
Iron-oxidizers (20 °C)		
48hr	<0.3	<0.3
7d	9.3	<0.3
14d	9.3	<0.3
21d	9.3	<0.3
Sulfur-oxidizers *	present	not present
Thiosulfate-oxidizers **	present	not present

* Thiobacillus thiooxidans

** Thiobacillus thioparus

Table 12.3.2 summarizes the microbial flora for the different experimental waters used in Phase 2. The experimental raw water is shown to have a more diverse microbial flora, in comparison to the experimental waters treated with chlorine and polyphosphate. As well, the experimental raw water had a considerably higher proportion of coloured microorganisms.

Water samples, treated with chlorine and polyphosphate did not show large populations of sulfate-reducing bacteria. This may be attributable to both the disinfecting power of chlorine and a highly aerobic environment.

The microbial flora of the experimental raw water, similar to that of the untreated water, shows sulfate and iron reducers as the most prevalent bacteria. Collection of the experimental raw water was from Pumphouse No. 1. This is identical, in location, from which the untreated water sample was obtained. Differences between the bacterial numbers of the two raw waters are due to differences in time and season of sampling, method and site of sampling, age of the water, and the water quality at the time of sampling.

Cultures enriched in Winogradsky's medium were examined for the presence of various species of iron bacteria. A change in pH was observed for inoculated mediums, whereby the pH increased from 5 to a range 7 to 8. The uninoculated medium did not exhibit this tendency. The turbidity of the inoculated mediums also increased. Microscopic examination of these cultures showed a fairly diverse population, the majority of which had heavy deposits of ferric iron. Air-dried slides of these cultures were treated with a dilute HCl solution (Allen, 1959).

Table 12.3.2
Microbial Flora for Different Water Quality Conditions and Corrosion Scales

Parameter	Untreated Supply Water (Sept., 89)	Corrosion Tubercles (Nov., 89)	Chamber Water Treated With Chlorine And Polyphosphate for Exposure to Ductile Iron			Chamber Water Treated With Chlorine And Polyphosphate for Exposure to Copper		
			Polyphosphate Concentrations			Polyphosphate Concentrations		
			5 mg/L as P	3 mg/L as P	1 mg/L as P	5mg/L as P	3mg/L as P	1 mg/L as P
Aerobic SPC (20 °C, 7d) cfu/mL	2.2 X10^6	2.0 X10^7	1.9 X10^5	3.5 X10^5	9.0 X10^5	1.3 X10^7	8 X10^9	7 X10^4
Anaerobic SPC (20 °C, 7d) cfu/mL	2.0 X10^1	2.0 X10^7	8.3 X10^1	1.4 X10^1	<300	5	4	1
Molds (20 °C, 7d) cfu/mL	4.8 X10^4	ND	1.5 X10^4	1 X10^4	5 X10^4	2 X10^6	ND	4 X10^4
Total Coliforms cfu/100mL	570	5.0 X10^4	92	4	3	<1*	<1	<1*
Fecal Coliforms cfu/100mL	ND	ND	<1	<1	<1	<1*	3	<1
Fecal Streptococcus cfu/100mL	<1	ND	<1	<1	<1	<1*	<1	<1
Iron-reducing Bacteria (MPN/mL)								
7d, 20 °C	ND	16000	11000	>11000	11000	9.3	200	0.7
14d, 20 °C	540	>24000	11000	>11000	4600	24	200	0.7
21d, 20 °C	1600	>24000	11000	>11000	4600	110	430	4
Sulfate-reducing Bacteria (MPN/mL)								
7d, 20 °C	ND	24	<0.3	<0.3	<0.3	0.4	<0.3	<0.3
14d, 20 °C	280	280	1.2	0.3	30	9.3	3	0.4
21d, 20 °C	340	280	70	40	40	15	7	0.9
Iron-oxidizing Bacteria	Present	Present	Present	Present	Present	Present	Present	Present
Sulfur-oxidizing Bacteria	Present	Present	Present	Present	Present	Present	Present	Present

ND= not determined. * Estimated Standard Plate Count

Microscopic examination of these treated slides showed the presence of: Leptothrix sp, Sphaerotilus sp, Gallionella sp, many small gram-negative aerobic rods and some gram-positive cocci.

The bacterial genera Leptothrix sp and Sphaerotilus sp are commonly referred to as sheathed bacteria. Bacteria in this group are characterized by the filamentous arrangement of their cells, which are enclosed within a sheath. The genus Sphaerotilus sp is the best known sheathed bacteria. In water containing iron, iron hydroxide may be deposited in or on the sheaths of these bacteria which turn a yellow-brown and become encrusted with ferric iron. In addition, Leptothrix sp also produces flocculent masses of hydrated ferric hydroxide.

The genus Gallionella, the most prevalent, is characterized by the forming of appendages that consist of an excreted substance. These bacteria have the ability to transform reduced soluble iron to insoluble ferric compounds, which can eventually accumulate to reduce the pipe's hydraulic capacity (Pelczar et al., 1977).

Gram-positive cocci include three families; Micrococcaceae and Streptococcaceae, which are aerobic or facultatively anaerobic, gram-positive cocci and the family Peptococcaeae, which are anaerobic, gram-positive cocci. All species are chemorganotrophic and are widely distributed in nature. Some species are pathogenic, while others are saprophytic.

The presence of these bacteria genera can serve to potentially intensify corrosion. The species Sphaerotilus, Leptothrix and Gallionella oxidize ferrous iron to insoluble ferric hydrate, which may be deposited to form tubercles commonly seen on the inside of water pipes. Stated earlier, was that the formation of tubercles may produce differential aeration or concentration cells due to the absorption of oxygen by microbial growths adhering to the deposit. Tubercles also support microhabitats for the proliferation of other harmful bacteria. The genus Gallionella, can concentrate chlorides in their deposits, which has the effect of a dilute HCl solution. Depending on the metal type, this can have a catastrophic effect.

These bacteria can also serve as catalysts in the transfer of soluble iron to an insoluble precipitate. This enables bacteria to have a direct role in the type of protective scales formed on the surfaces of iron metals (AWWA, 1985).

Cultures grown in Starkey's medium were examined for the presence of sulfur oxidizing bacteria. The pH of these cultures decreased from 7.5 to between the range of 6.0 to 4.0. Microscopic examination revealed the presence of gram-negative, rod shaped bacteria. These bacteria were presumptively identified as Thiobacillus thiooxidans. It is presumed that the decrease in pH was due to the oxidation of elemental sulfur. The uninoculated control did not exhibit this tendency.

Sulfur oxidizing bacteria were reported to be present in all water samples examined. Sulfur oxidizers, such as Thiobacillus, oxidize sulfides to sulfates, thus producing sulfuric acid. They are also known to oxidize ferrous iron to ferric. However, it is their ability to produce sulfuric acid that makes them corrosive to metals.

The B_{10} Broth medium was originally developed for cultivation of heterotrophic iron-reducing soil bacteria. Heterotrophs shown to be involved in iron reduction include: *Bacillus*, *Pseudomonas*, *Proteus*, *Alcaligenes*, *Clostridium*, and *Enterobacteriaceae*. For some microorganisms, it has been shown that nitrate will inhibit Fe^{3+} reduction and nitrate reductase negative mutants lose their ability to reduce Fe^{3+}. This has resulted in the theory that iron reduction may be linked to the organism's nitrate reductase system (Allen, 1959). The mechanism is thought to be such that nitrate in the medium may displace iron from the enzyme, nitrate reductase (Ehrlich, 1981). It has been shown that iron reduction by Enterobacteriaceoie, Bacillacae, *Pseudomonas*, and *Micrococcus* can be inhibited in the presence of nitrate and chlorate (Ehrlich, 1981). Other organisms can reduce iron and do not process nitrate reductase (Ehrlich, 1981). This includes *Bacillus pumilus*, *Bacillus sphaericus*, *Clostridium butyricum*, *Staphylococcus aureus*. Some fungi such as *Alternania* and *Fusarium* have also been shown to reduce iron (Ehrlich, 1981).

Although they are not true iron bacteria, many heterotrophic bacteria can precipitate iron from solution. These organisms may produce a reducing environment, by forming metabolic end products that can reduce iron and manganese oxidation products. In essence, the formation of iron precipitates may be a waste product for these organisms. Thus, their ability to influence corrosion is similar to that of iron bacteria (Lee et al., 1980).

Experimental water samples, treated with chlorine and polyphosphate and exposed to ductile iron, have the highest populations for iron-reducing bacteria. This is attributed to the availability of the substrate, iron. Some anaerobic bacteria derive their energy in the reduction of iron for metabolic activity. The experimental raw water showed similar bacterial species. This may be attributed to biofilm contamination from the submarine supply pipeline. Iron-reducing bacteria were not present in significant numbers in those water samples exposed to copper. This may be explained by the lack of substrate and possible inhibition, by the increase in copper concentration as a result of copper corrosion.

Microbial examination of a section of corroded pipe removed from Pumphouse No. 1, for exposure to the treated water, showed slightly different results to that of the experimental raw water. Heterotrophic iron-reducers were present in significantly higher numbers than the sulfate reducing bacteria. Iron oxidizers enrichments showed growth plus oxidation of Fe^{2+} in 1/10,000 dilutions of corrosion scale and contained Leptothrix, Gallionella, and Sphaerotilus sp. Sulfur oxidizers enrichments showed growth with a decrease in pH at 1/10,000 dilutions and contained T. thioparus. Cultures grown at 2 to 8 °C also produced similar results, indicating a psychrotolerent, metabolically active population. Overall, corrosion tubercles had significantly higher microbial populations than did the experimental raw water, including numbers of total coliforms. The ability of an organism to attach to the metal surface increases its access to nutrients from the water column (Ridgeway and Olson, 1981), as well as it changes its disinfection susceptibility. Shown is tubercles protect potentially pathogenic organisms from chlorine's disinfecting power. Such an effect will allow for microorganisms to grow and proliferate in the scale growth on the surfaces of pipes.

The distribution system was sampled only once. Corrosion-causing and corrosion intensifiying bacteria were present in low concentrations in untreated water and absent in the treated water. Corrosion scales, however, showed very high concentrations of corrosion-causing and corrosion-intensifying bacteria. This was not unexpected, for the City has experienced difficulties in the past in maintaining a adequate chlorine residual throughout its distribution system. The chlorine residual, present primarily as free chlorine, will react with the corrosion scale present on the inside of pipes, resulting in its decline and possibly the loss of residual protection. The loss of chlorine residual combined with its inability to prenetrate into the corrosion scale enables bacteria capable of causing corrosion to proliferate. Based on the microbial results from the examination of corrosion scales, it is reasonable to assume the City of Yellowknife's corrosion problem is attributable to the chemical corrosivity of the supply water, combined with the presence of corrosion-causing and corrosion-intensifying bacteria. Although, additional support data is needed to futher evaluate the significance of the bacterial numbers reported.

13.0 Edmonton Corrosion Study

13.1 Objective

To assess the severity of Yellowknife's corrosion problem, similar studies were conducted using Edmonton's treated water. Both in-situ and batch corrosion tests, identical in procedure to the Yellowknife tests, were performed using the material ductile iron. Results of these tests are compared to the Yellowknife results for assessment of its corrosion problem.

13.2 Methodology

13.2.1 Corrosion Measurement

Corrosion measurement was by the weight loss determination method, using coupons identical to those used in the Yellowknife study.

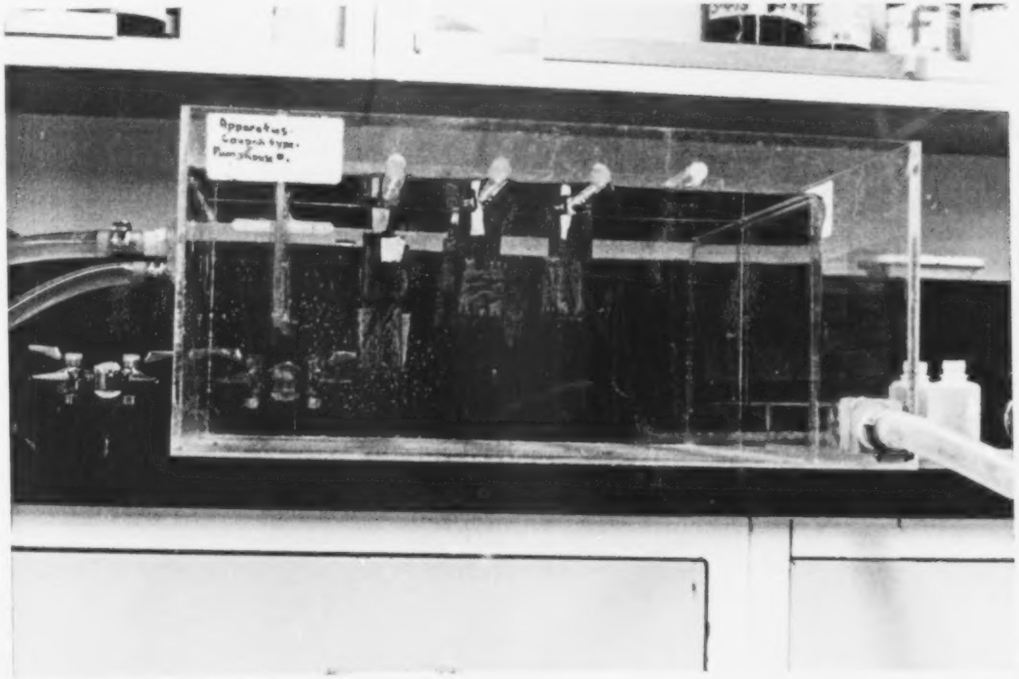
13.2.2 Batch Study: Experimental Setup

Used as the experimental apparatus, were the Plexiglas batch reactors of Phase 2 of the laboratory study. The apparatus set-up was identical to that used in the Phase 2 laboratory study.

13.2.3 In-situ Corrosion Study: Experimental Setup

Used for the in-situ corrosion study, was the apparatus set-up used in Phase 1 of the Yellowknife study. The apparatus set-up consisted of a constant head tank and a single coupon holding tank (Figure 13.2.3.1). The apparatus was connected to a cold water tap in the basement laboratory of

Figure 13.2.3.1
Experimental Apparatus, In-situ Corrosion Study
Edmonton, Alberta


Apparatus.
Coupon type.
Pumphouse

the Newton Research Building. The average flow velocity, to which the coupons were exposed, averaged 0.0011 m/s.

13.2.4 Experimental Water

Edmonton's treated water was used as the experimental water. The experimental water used in both, the batch and in-situ study, was from the cold water tap in the basement laboratory of the Newton Research Building. The origin of this water was from the Rossdale Water Treatment Plant, Edmonton.

13.2.5 Test Samples

The test specimens used were ductile iron metal coupons and they were identical to those used in the Yellowknife study.

13.2.6 Water Analysis

The flow of treated water into the apparatus was periodically sampled and analyzed using the same analytical techniques as in the Yellowknife study.

13.3 Water Quality Results for Edmonton's Treated Water

Table 13.3.1 summarizes the range of water quality of Edmonton's treated water as sampled from the cold water tap in the basement laboratory of the Newton Research building, for the duration of the experiments. Edmonton's treated water is moderately hard, slightly alkaline, well buffered, and with a moderate amount of dissolved solids.

Table 13.3.1
Water Quality Characteristics for Edmonton's Treated Water

Parameter (mg/L)	Edmonton's Treated Water (range)
Calcium	28.46 to 34.69
Chlorine Residual	1.8 to 2.2 as monochloramine
Conductivity (umhos/cm)	150 to 230
Magnesium	10.87 to 12.22
pH	7.78 to 8.15
Sodium	3.06 to 9.56
Sulfate	60.1 to 77.5
Temperature	7 to 15.5
Total Alkalinity (as $CaCO_3$)	42.1 to 61.4
Total Hardness (as $CaCO_3$)	107 to 120
Turbidity (NTU)	1.7 to 4.8

13.4 Experimental Schedule

13.4.1 Batch Study

Figure 13.4.1.1 is the experimental schedule for the removal of ductile iron coupons, for the Batch Study. Sample sets consisted of two coupons each and were removed weekly. The duration of the tests was approximately four weeks.

13.4.2 In-situ Study

Figure 13.4.2.1 is the experimental schedule for the removal of ductile iron coupons, for the in-situ study. Sample sets consisted of three coupons each and were removed weekly. The duration of the tests was approximately four months.

13.5 Statistical Analysis of the Corrosion Rate Data for the Batch and In-situ Study

Tables 13.5.1.1 and 13.5.2.1 provide a summary of the statistical analysis of the corrosion rate data for batch and in-situ studies. Included in each table is the average, standard deviation, range, and calculation of outliers using the Q-test for a 90% probability for each sample set.

13.6 Specific Weight Losses

13.6.1 Batch Study

Figure 13.6.1.1 shows the specific weight losses with time for ductile iron exposed to Edmonton's treated water. The major difference between the batch and in-situ corrosion studies were the flow velocities to which

Figure 13.4.1.1
Experimental Schedule: Batch Study

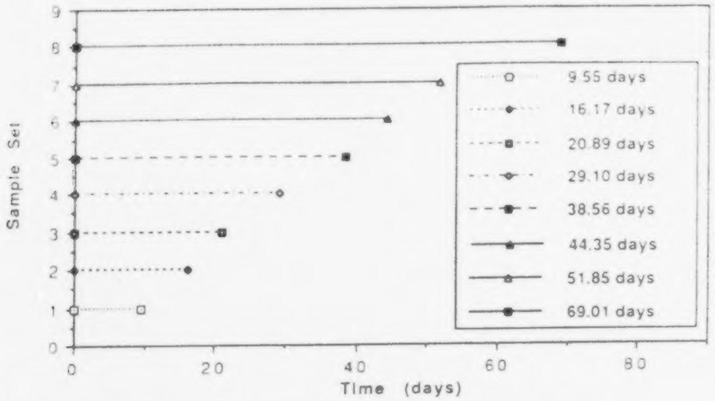


Figure 13.4.2.1
Experimental Schedule: In-situ Study

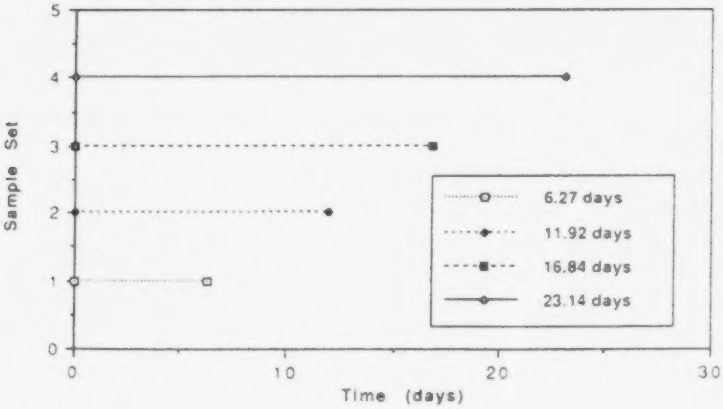


Table 13.5.1.1
Statistical Analysis of the Ductile Iron Corrosion Rate Data for the Batch Study

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
2	6.27	10.65	0.3041	10.85-10.43	N/A
2	11.92	9.18	0.0141	9.19-9.17	N/A
2	16.84	6.50	0.0100	6.50-6.49	N/A
2	23.14	6.06	0.0141	6.07-6.05	N/A

Table 13.5.2.1
Statistical Analysis of the Ductile Iron Corrosion Rate Data for the In-situ Study

No. of Coupons	Detention Time (days)	Average g/(m^2 d)	Standard Deviation g/(m^2 d)	Range g/(m^2 d)	Outliers
3	9.55	2.39	0.0951	2.48-2.29	N/A
3	16.17	2.64	0.0990	2.81-2.50	N/A
3	20.89	2.62	0.0875	2.72-2.55	N/A
3	29.10	2.50	0.0361	2.53-2.46	N/A
3	38.56	2.47	0.0854	2.56-2.39	N/A
3	44.35	2.18	0.1079	2.30-2.10	N/A
3	51.85	2.26	0.0894	2.34-2.14	N/A
3	69.01	1.96	0.0418	2.01-1.93	N/A

the coupons were exposed. For the batch study, the water was continuously aerated, exposing the coupons to very turbulent conditions. For the in-situ study, metal coupons were exposed to very low flow conditions (0.0011 m/s). Velocity has been to shown to have varying effects on the corrosion rates of different metals depending on pH, oxygen concentrations, galvanic couplings, polarization, and electrode potential. Eliassen et al. (1956) studied the effects of velocity on the corrosion of steel and found the corrosion rate to increase with increasing velocity. The specific weight losses were much higher for the batch study, but this was to be expected since the exposure conditions were much more turbulent. For example, the specific weight losses of ductile iron for the batch study after the second and fourth week were 115 and 160 g/m^2. Compared to the in-situ study, the specific weight losses after the second and fourth week were 40 and 70 g/m^2. The percent differences in weight losses between studies after the second and fourth week are 65 and 56 percent. Visual inspection showed corrosion damage to have occurred uniformly over the surfaces of coupons. This indicates uniform corrosion.

13.6.2 In-situ Study

Figure 13.6.2.1 shows the specific weight losses with time, for ductile iron exposed to Edmonton's treated water. As expected, the weight losses initiaaly increased uniformly, but after the seventh week the losses began decreasing. The specific weight losses after the second and fourth week were 40 and 70 g/m^2. Visual inspection showed corrosion damage to have occurred uniformly over the surfaces of coupons (Figure 13.6.2.2). This indicates uniform corrosion.

Figure 13.6.2.2
Corrosion Damage to Ductile Iron Coupons
Exposed to Edmonton's Treated Water

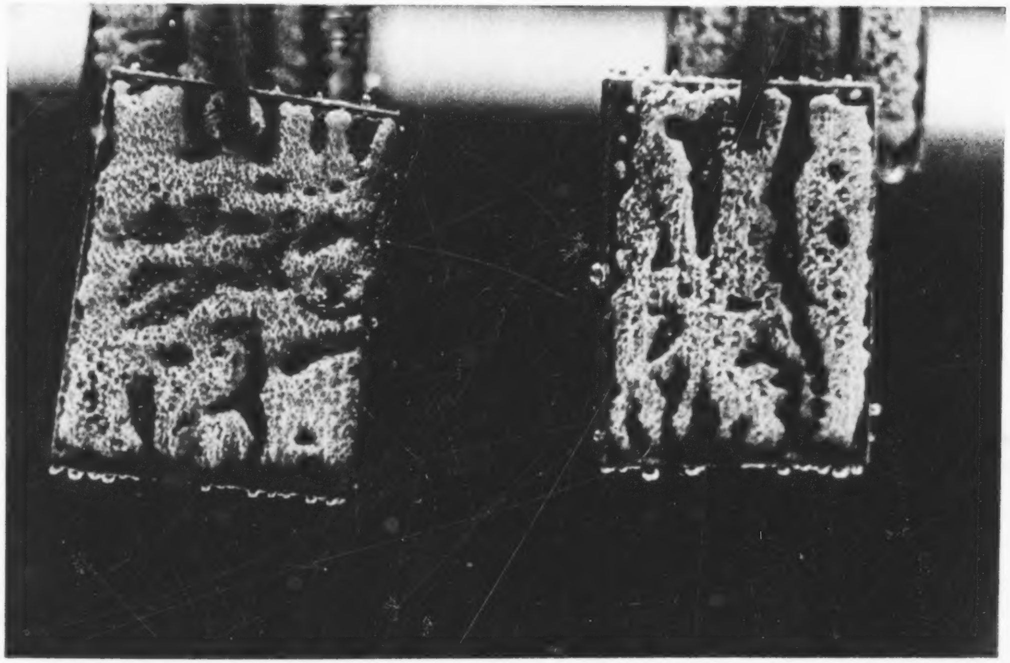


Figure 13.6.1.1
Specific Weight Losses Versus Time for Ductile Iron Exposed to Edmonton's Treated Water, Batch Study

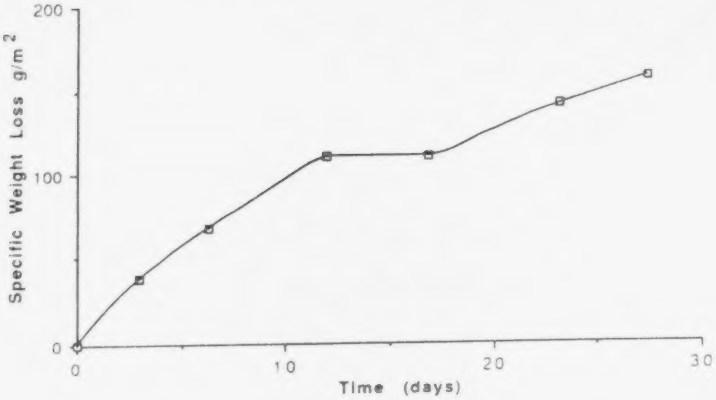
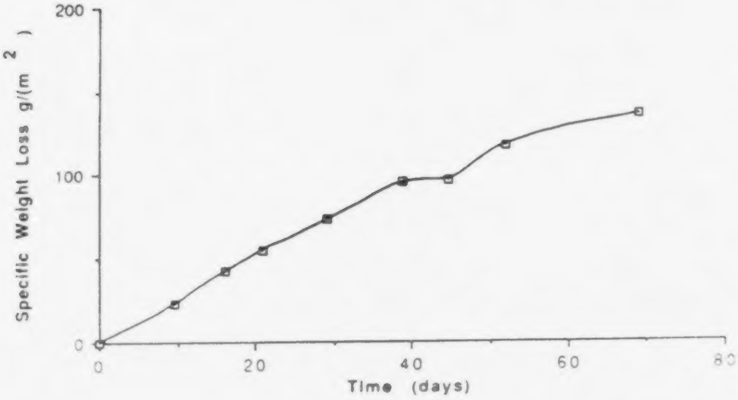


Figure 13.6.2.1
Specific Weight Losses Versus Time for Ductile Iron Exposed to Edmonton's Treated Water, In-situ Study



13.7 Corrosion Rates

13.7.1 Batch Study

Shown in Figure 13.7.1.1 are the corrosion rates versus time for ductile iron exposed to Edmonton's treated water. The corrosion rates for the batch study in comparison to the in-situ study were much higher, with the differences being attributable to the different flow velocities. For example, the corrosion rates after the fourth week for the batch and in-situ study were 5.71 and 2.50 $g/(m^2\ d)$, for a difference of 56%. The corrosion rates are also shown decreasing with time. This is attributed to the formation of scale on the surfaces of coupons. The corrosion rate reached a constant value of 5.71 $g/(m^2\ d)$ after four weeks of exposure.

The range of flows in most pipes varies from none to highly turbulent. Considering this, it would be reasonable to assume the corrosion rates obtained for the batch study are for a worst case scenario. For highly turbulent conditions corrosion is greatly increased. The result is that the service life of the piping is greatly reduced. However, it is desirable to have a moderate flow velocity in the piping to produce a turbulent flow condition to, in turn, provide an effective calcium carbonate scale, or to form and maintain good corrosion protective films of phosphates or silicates (AWWA, 1985). The flow velocity should be 0.6 m/s or greater.

13.7.2 In-situ Study

Figure 13.7.2.1 shows the corrosion rates versus time for ductile iron, exposed to Edmonton's treated water. Unlike the results for the

Figure 13.7.1.1
Corrosion Rates Versus Time for Ductile Iron Exposed to Edmonton's Treated Water, Batch Study

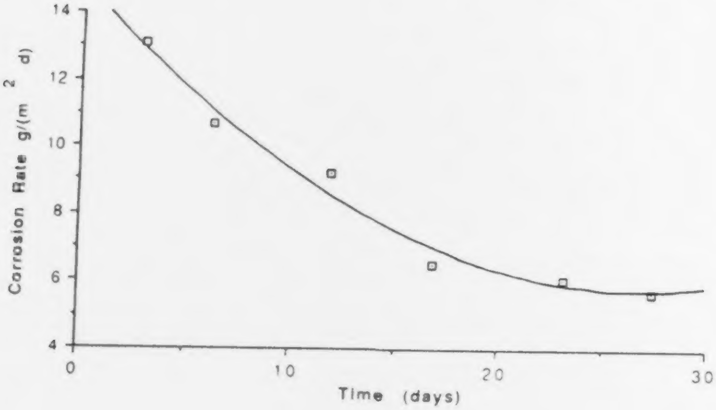
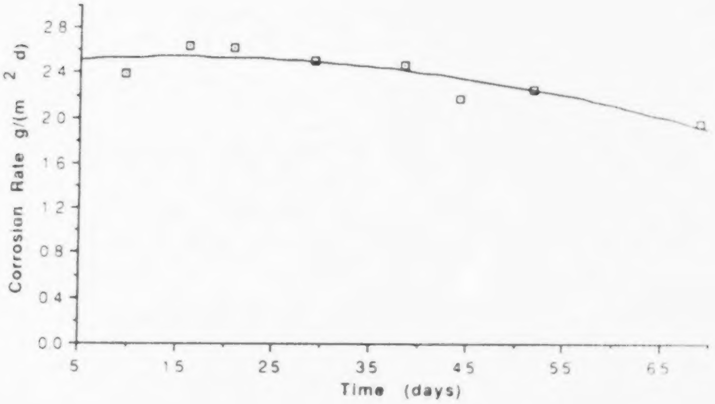


Figure 13.7.2.1
Corrosion Rates Versus Time for Ductile Iron Exposed to Edmonton's Treated Water, In-situ Study



Yellowknife in-situ corrosion study (Phase 1), high initial corrosion rates were not observed. Rather, the corrosion rates were relatively constant after the first week of exposure, but after six weeks slowly decreased with time. According to AWWA (1985) corrosion rates of 2.5 $g/(m^2\ d)$, or less for ductile iron are considered low and are a general indication of satisfactory service life. Only during the initial four weeks of exposure did the corrosion rates slightly exceeded AWWA's limit. Beyond four weeks of exposure, the corrosion rates had decreased below 2 $g/(m^2\ d)$, with the rate continuing to decrease. It would appear that the service life of ductile iron is not severely affected, based on the long term corrosion rates obtained.

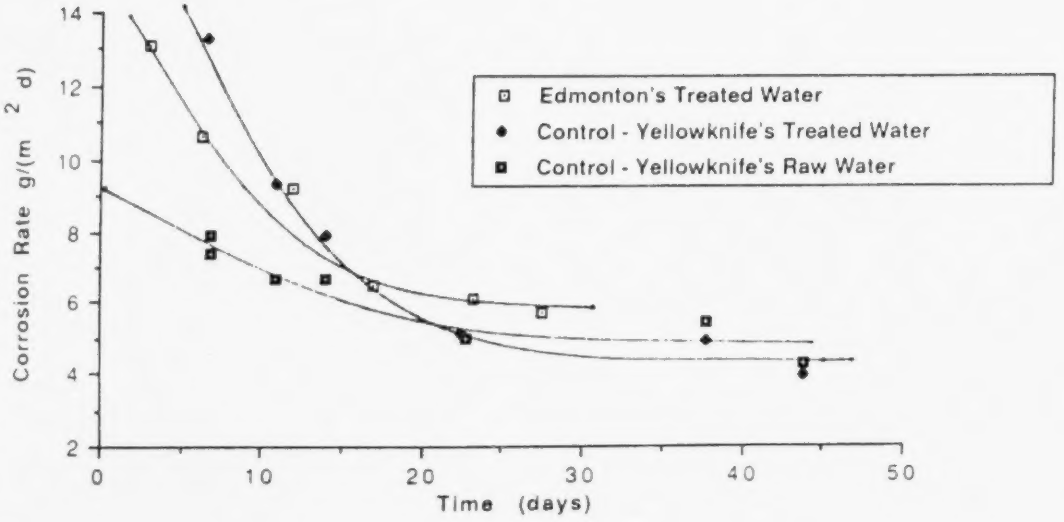
13.8 Comparison of Yellowknife's Corrosion Problem to That of Edmonton, Alberta.

13.8.1 Comparison of Batch Studies

Figure 13.8.1.1 shows the corrosion rates versus time of ductile iron, for exposure to Yellowknife's raw and treated waters and to Edmonton's treated water. Except for differences in water quality between the two communities, the exposure conditions by which the tests were performed were similar. That is, the physical characteristics such as: temperature and flow conditions were similar.

Table 13.8.1.1 summarizes the water quality characteristics associated to each community's potable water. Comparison of the water quality shows Edmonton's treated water to be moderately hard in comparison to Yellowknife's very soft water. The City of Edmonton presently chlorinates its potable water to obtain a total residual chlorine concentration between

Figure 13.8.1.1
Comparison of the Corrosion Rates of Ductile iron for Exposure to Yellowknife's Raw and Treated Waters and to Edmonton's Treated Water.



the range of 1.8 to 2.2 mg/L as monochloramines. This is approximately twice the value to which the City of Yellowknife chlorinates its potable water, and the residual exists primarily as free chlorine. However, in the laboratory batch tests, chlorine was rapidly removed from solution as a gas in aerating the water. As a result, chlorine only initially intensified the corrosion of ductile iron not passivated by corrosion products. The sulfate concentration also averaged 30 times greater for Edmonton's treated water versus Yellowknife's treated water. Sulfate has been reported to increase the corrosion of metals (AWWA, 1985).

Shown Figure 13.8.1.1 is the corrosions rates of the batch study similar to the control simulating Yellowknife's treated water. Test results of the batch study suggest Yellowknife's treated water is equally corrosive as Edmonton's treated water. The data shows there is not a significant difference between the corrosivity of the two treated waters. Regasrdless of the differences in water quality between each community, the corrosion rates were relatively the same. The similarity between the corrosion rates may be due to the same influencing effect velocity had on corrosion in aerating each water.

13.8.2 Comparison of In-situ Studies

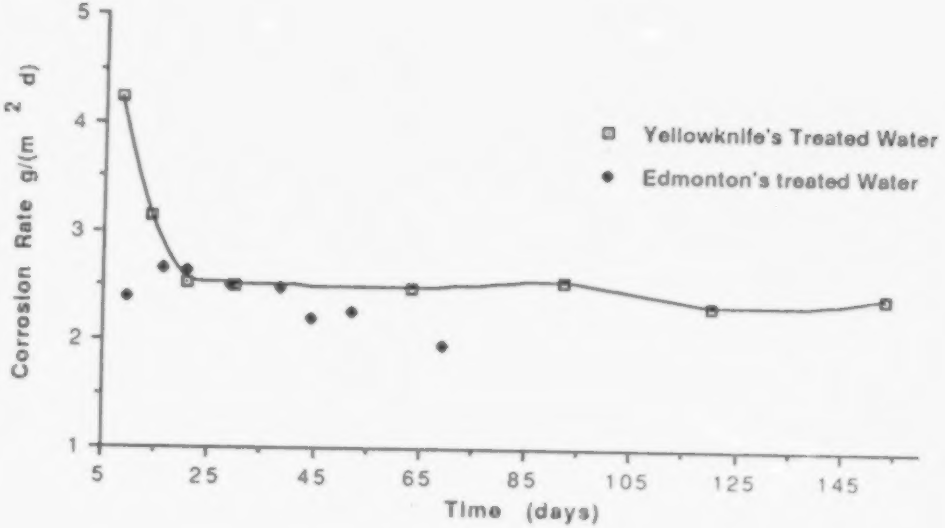
Figure 13.8.2.1 shows the corrosion rates versus time of ductile iron, for exposure to Yellowknife's and Edmonton's treated waters. The corrosion rates were similar between the treated waters, until after the second month, when Edmonton's treated water began showing lower rates of corrosion. The corrosion rates, after the tenth week for

Table 13.8.1.1

Comparison of Water Quality Between Treated Waters for the City of Yellowknife and the City of Edmonton.

Parameter (mg/L)	Edmonton's Treated Water	Yellowknife's Treated Water
Calcium	28.46 to 34.69	4.37 to 5.46
Chlorine Residual	2.0 mg/L as monochloramine	1.0 mg/L as free chlorine and monochloramine
Dissolved Oxygen	Saturated	Saturated
pH	7.78 to 8.15	6.8 to 7.5
Sulfate	71.7 to. 77.5	1.8 to 3.9
Temperature (°C)	5	5
Total Alkalinity (as $CaCO_3$)	42.4 to 61.4	16.6 to 20.2
Total Hardness (as $CaCO_3$)	107 to 120	18.4 to 19.8

Figure 13.8.2.1
Corrosion Rates Versus Time for Ductile Iron Exposed to Both Yellowknife's Treated Water and Edmonton's Treated Water



Edmonton's and Yellowknife's treated waters, were 1.96 and 2.50 g/(m^2 d), for a difference of 22%.

Similar to the batch study, initially the corrosion rates for the two treated waters were not significantly different. However, after the fourth week, the corrosion rates for Edmonton's treated water began to decrease in comparison to the rates for Yellowknife's treated water.

The results for the batch and in-situ studies suggest Edmonton's treated water is either equally or slightly less corrosive than Yellowknife's treated water, and that this is dependent on the flow conditions. However, the City of Edmonton is, by no means, experiencing the corrosion problems as is the City of Yellowknife. This can be attributed to two reasons. Firstly, are the differences in each water's tendency to precipitate $CaCO_3$. Edmonton's treated water has a Langelier index (LSI) of -0.40, indicating the water is moderately aggressive. That is, the water is only slightly undersaturated and may, from the local increase in pH at the pipe's surface due to corrosion precipitate $CaCO_3$. Yellowknife's treated water has a LSI value of -2.63 indicating the water is very aggressive. The treated water is undersaturated with respect to $CaCO_3$ and will definitely dissolve $CaCO_3$. Secondly, is that Edmonton only three years ago altered its water treatment program to produce a water that is slightly aggressive with respect to $CaCO_3$. In the past, the water was conditioned to deposit $CaCO_3$.

14.0 Comparison of the Chemicals Shown Most Promising

Identified are those parameter settings shown most promising for each inhibitory chemical for reducing ductile iron and copper corrosion. The water quality settings for the most promising chemicals are compared to the control with chlorine, as a base comparison.

The relative corrosion rates of the chemicals compared were generally the same after a 25 day exposure time. This observation is believed to be the influence of the environment, rather than the inhibitory effect of the chemicals. Turbulent conditions and the water saturated with respect to dissolved oxygen are believed to be the factors responsible for controlling the corrosion rates. Sufficient mixing was provided that the transfer of the inhibitory chemical to the metal surface was not impaired. However, the deposition of the insoluble salts and the rate of scale loss from the surface was likely controlled by the turbulent conditions. Consequently, this may have restricted the inhibitory action of the chemicals in further reducing the corrosion rates below those observed. As a result, comparison of the inhibitory chemicals is restricted to the initial two weeks of exposure, for evaluation of their effectiveness.

Figure 14.1 shows three chemicals as potentially promising for reducing ductile iron corrosion. These chemicals are sodium hexametaphosphate at a concentration of 1.0 mg/L as P, sodium silicate at a concentration of 6.9 mg/L as SiO_2, and the combination of the conditioning chemicals, lime, carbon dioxide and sodium hydroxide at a

Figure 14.1
Bar Graph Comparison of the Chemicals Shown Most
Promising from the Ductile Iron Tests

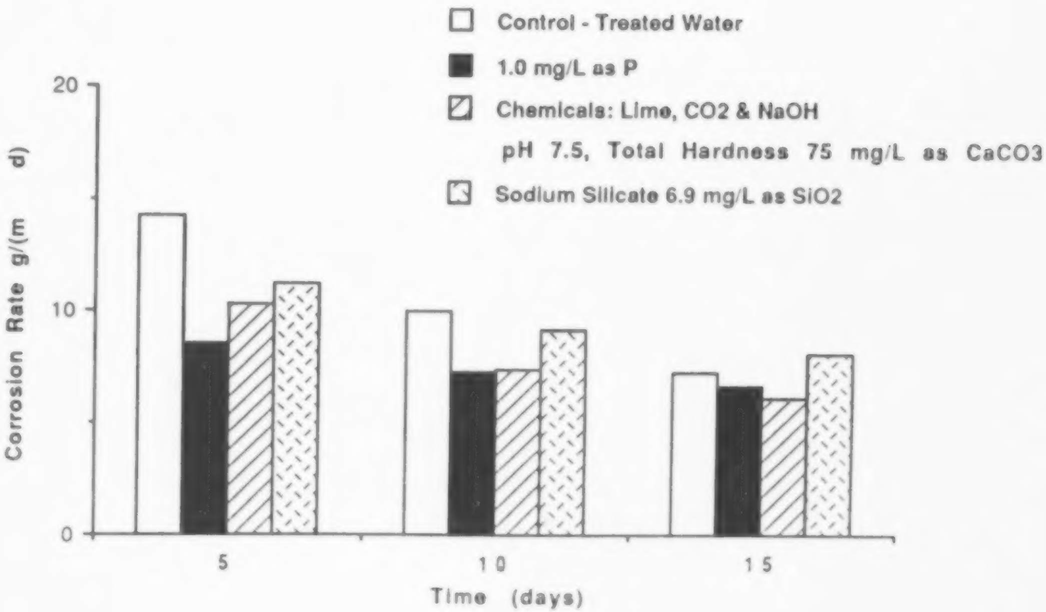


Table 14.1
Percent Ductile Iron Corrosion Rate Reductions
for Each Chemical Relative to the Control With Chlorine

Time (days)	Inhibitory Chemical Percent Difference (%)		
	Polyphosphate 1 mg/L as P	Sodium Silicate 6.9 mg/L as SiO2	Lime, Carbon Dioxide, & Sodium Hydroxide pH – 7.5 & Hardness 75 mg/L as CaCO3
5	-40.6	-21.0	-28.0
10	-27.0	-8.0	-26.0
15	-8.2	+11.0	-16.0

pH of 7.5 and total hardness concentration of 75 mg/L as $CaCO_3$. All of which, to a varying degree, reduced initial corrosion. Polyphosphate, initially, was the most effective, whereas, sodium silicate was the least effective. Shown in Table 14.1 are the percent corrosion rate reductions for each chemical relative to the control with chlorine.

The combination of lime, carbon dioxide and sodium hydroxide was the most effective for reducing ductile iron corrosion. The best water quality in testing these chemicals was for a pH 7.5, a total hardness of 75 mg/L as $CaCO_3$ and a resultant average alkalinity of 160 mg/L as $CaCO_3$. However, the calcium carbonate precipitation potential at this setting exceeded Merrill and Sank's (1978) recommended maximum value of 10 mg/L as $CaCO_3$ for avoiding excess $CaCO_3$ deposition. Therefore, the best setting for the laboratory study is not the ideal setting for use in the distribution system. The laboratory study was limited to demonstrating that conditioning the water, to promote the precipitation and establishment of coatings of $CaCO_3$ on the metal's surface, could effectively reduce corrosion. The study was unable to provide accurate inhibitor dosages for the use of these conditioning chemicals in the water distribution system. Instead, adjustment of the water quality to best satisfy the criteria for a well conditioned water, suggested by Merrill and Sanks (1978), is to be used as a guideline for their use in the distribution system.

The study does not recommend the use of pH adjustment chemicals alone, for reducing ductile iron corrosion. Firstly, ferrous metals are not well protected in low mineralized waters by pH adjustment alone, unless the pH is above 8.5, which exceeds the Canadian Drinking Water Guidelines (GCDWQ, 1989). Secondly, Yellowknife's supply water lacks sufficient calcium concentration, such that pH adjustment alone, will not promote the precipitation of a protective coating of $CaCO_3$ needed for reducing corrosion.

Figure 14.2 shows the comparison of the optimum water quality settings for each inhibitory chemical in reducing copper corrosion. Shown, are polyphosphate at a concentration of 1.0 mg/L as P, sodium hydroxide for a pH setting 8.5, and the combination of lime, carbon dioxide and sodium hydroxide, as effective, in varying degrees, in reducing copper corrosion for the exposure time investigated. With the exception of sodium carbonate, the above inhibitory chemicals reduced copper corrosion rates to rates lower than those observed for the control with chlorine. Shown in Table 14.2 are the percent corrosion rate reductions for each chemical relative to the control with chlorine. The corrosion rates for sodium carbonate were observed to increase after a two week exposure time, to suggest a change in the environment to intensify corrosion.

Unlike the ductile iron results, is the water quality changes associated to the liquid's retention time for the copper experiments improved the inhibitory performance of particular chemicals. For example, the pH adjustment chemicals were most influenced by the water quality changes. For a more accurate evaluation of these chemicals, a pilot plant study is needed to determine their in-situ performance for the best control parameter settings, as determined from this laboratory study.

Selection of a chemical for reducing copper corrosion should take into consideration that chemical's performance in reducing ductile iron corrosion. The laboratory study clearly shows that ductile iron is more

Figure 14.2
Bar Graph Comparison of the Chemicals Shown Most Promising from the Copper Tests

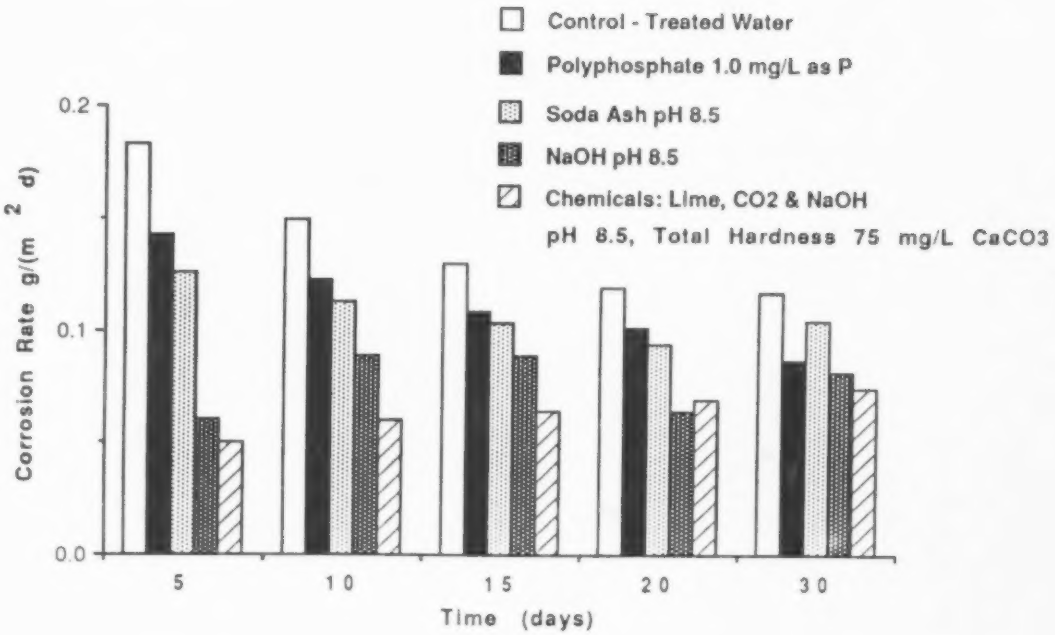


Table 14.2
Percent Copper Corrosion Rate Reductions for Each Chemical Relative to the Control With Chlorine

Time (days)	Inhibitory Chemical Percent Difference (%)			
	Polyphosphate 1 mg/L as P	Soda Ash pH 8.5	Lime, Carbon Dioxide, & Sodium Hydroxide pH - 8.5 & Hardness 75 mg/L as CaCO3	Sodium Hydroxide pH - 8.5
5	-21.9	-31.1	-72.7	-67.2
10	-18.1	-24.0	-60.0	-40.0
15	-16.0	-20.0	-50.0	-17.4
20	-15.0	-20.8	-41.7	-45.8
30	-25.4	-11.0	-36.4	-30.5

susceptible to corrosion and presents a greater problem in the maintenance and operation of the distribution system. Copper corrosion, however, cannot be neglected, for it poses an important aesthic concern for the consumer. Selection of the inhibitor must therefore be able to effectively reduce both ductile iron and copper corrosion.

The basis for the selection of one of these inhibitory chemicals for reducing corrosion of both metals is presented in the recommendations.

15.0 Conclusions

The following is a summary of the major conclusions of this research.

15.1 Phase 1, Yellowknife In-situ Study

- Chemical treatment of Yellowknife's river water from the addition chlorine, primarily as free chlorine, hydrofluosilicic acid, and during the winter, heat, substantially increases the water's corrosivity.

- Ductile iron corrosion increased by 40 % from chemical treatment of the water.

- Copper corrosion increased by 65 % from chemical treatment of the water.

- Corrosion of copper for exposure to the untreated and treated water is low, and would not seriously affect the service life of copper piping.

- Corrosion of ductile iron for exposure to the untreated and treated water is moderate, and would moderately reduce the service life of ductile iron piping.

- Based on the long term average corrosion rates, the estimated time period before 50% of the pipe wall is lost for a 150 mm diameter ductile iron pipe with a wall thickness of 6.4 mm exposed to the treated water is approximately 24 years.

- Based on the long term average corrosion rates, the estimated time period before 50% of the pipe wall is lost for a 150 mm diameter ductile iron pipe with a wall thickness of 6.4 mm exposed to the untreated water is approximately 33 years.

- Metal corrosion decreases with time and that this is attributed to the protective properties of corrosion scales.

15.2 Phase 2, Laboratory Batch Study

The laboratory study was an effective means for making an initial appraisal of the effectiveness of the various chemicals considered. The study, however, did not provide for accurate estimates of inhibitor dosages, for use in the water distribution system. Instead, the study was useful in showing the tendency of these chemicals for reducing ductile iron and copper corrosion. The performance of these chemicals are site specific and depend highly on the conditions under which they are applied. To fully account for in-situ conditions within the distribution system requires doing a pilot plant study. Realistically, a pilot plant study is the next step beyond doing a laboratory batch study before selecting an inhibitor for use in the distribution system.

15.3 Polyphosphate

15.3.1 Ductile Iron

- Polyphosphate was effective at low concentrations (1 mg/L and 3 mg/L as P) in reducing initial ductile iron corrosion in comparison to the control with chlorine.

- The difference between the ductile iron corrosion rates at the concentrations 1 mg/L and 3 mg/L as P, were not significantly different at a 95% confidence level.

- Polyphosphate at the concentration 5 mg/L as P caused adverse effects on the initial development of protective scales, producing the problem of "red water." Polyphosphate at this concentration increased corrosion and was not initially beneficial in reducing ductile iron corrosion.

- The tendency was for ductile iron corrosion to increase with increasing polyphosphate concentration.

- The total hardness and polyphosphate concentration of each setting decreased, with the magnitude increasing with increasing polyphosphate concentration.

15.3.2 Copper

- Copper corrosion was shown independent of polyphosphate concentration. There was little difference between the corrosion rates of the concentrations: 1, 3 and 5 mg/L as P.

- Polyphosphate, however, was effective in reducing copper corrosion by 22 and 38 % in comparison to the controls with and without chlorine for 4 weeks of exposure.

- The total hardness and polyphosphate concentration of each setting increased slightly for the liquid's weekly retention time to indicate polyphosphate had not deposited on the surfaces of copper coupons.

15.4 pH Adjustment Chemicals: Sodium Carbonate and Sodium Hydroxide.

15.4.1 Ductile Iron

- pH adjustment chemicals were not effective in reducing ductile iron corrosion between the pH range of 7.5 to 8.5. Yellowknife's supply water has an insufficient calcium concentration desirable for depositing a protective coating of $CaCO_3$, as result of pH adjustment.

- The pH setting 7.5, least affected from changes in water quality, was only slightly effective in reducing initial corrosion in comparison to the control with chlorine.

- Ductile iron corrosion increased from increasing the pH from 7.5 to 8.5. pH adjustment chemicals are not recommended for inhibition of ductile iron corrosion in water distribution systems.

15.4.2 Copper

- Copper corrosion is pH dependent and the pH adjustment chemicals were effective in reducing copper corrosion in comparison to the controls, with and without chlorine.

- Copper corrosion was shown to decrease with increasing pH and alkalinity.

15.5 Conditioning Chemicals; Lime, Carbon Dioxide and Sodium Hydroxide.

15.5.1 Ductile Iron

- The tendency was for ductile iron corrosion to decrease with decreasing pH and increasing hardness concentration. The best setting was the setting: pH 7.5, total hardness concentration 75 mg/L as $CaCO_3$ and a resultant alkalinity of 160 mg/L as $CaCO_3$. This setting best corresponded to Merrill and Sanks recommended water quality for the deposition of a protective coating of $CaCO_3$.

- Calcium carbonate was observed to deposit on the surfaces of ductile iron coupons at the hardness concentrations: 50 and 75 mg/L as $CaCO_3$, regardless of pH setting.

- Protective coatings formed at pH's 8.0 and above were less protective in comparison to those formed at pH 7.5, regardless of hardness concentration.

15.5.2 Copper

- Copper corrosion decreased with increasing pH and alkalinity. Increasing the calcium concentration appeared to have little effect in reducing copper corrosion.

- No coatings of $CaCO_3$ were observed to form on the surfaces of copper coupons.

- The pH setting 8.5, regardless of hardness concentration, was most favourable in reducing copper corrosion.

15.6 Sodium Silicate

15.6.1 Ductile Iron

- The tendency was for ductile iron corrosion to increase with increasing silicate dosages between the range of 6.9 to 21.0 mg/L as SiO_2. The best dose concentration was 6.9 mg/L as SiO_2 and this dosage only slightly reduced initial corrosion in comparison to the control with only chlorine.

- Silicate dose concentrations for 10.0 mg/L as SiO_2 and higher increased corrosion and were not effective in comparison to the control with only chlorine.

15.6.2 Copper

- The tendency was that copper corrosion decreased slightly with increasing silicate concentration.

- The silicate concentrations 2.1, 4.0 and 5.9 mg/L as SiO_2 were not effective in reducing copper corrosion in comparison to the control with only chlorine.

15.7 Microbial Results

- Corrosion-causing and corrosion-intensifying bacteria were present in low concentrations in the untreated water sample, collected from Pumphouse No. 1. The bacteria most prevalent in the untreated water were the species: thiosulfate and heterotrophic iron reducing bacteria.

- Microbiological analysis of the treated water, for the location sampled, showed very different results to that of the untreated water sample. Absent were many of the bacterial species identified in the untreated water. The absence of bacteria is attributed to the disinfecting power of chlorine.

- Microbial examination of corrosion scales removed from a section of pipe exposed to the treated water, showed significantly higher bacteria populations than did the untreated and treated water samples. The bacteria most prevalent in the corrosion scales was iron reducing bacteria. Although, also present in high numbers were total coliforms.

- Although the results represent an one time sampling of the distribution system, nevertheless based on the microbial results from the examination of corrosion scales it is reasonable to assume bacterial contribute to Yellowknife's corrosion problem.

15.8 Comparison of Edmonton's and Yellowknife's Batch and In-situ Corrosion Studies.

- Comparison of the batch studies showed Edmonton's treated water to be equally corrosive to Yellowknife's treated water. The similarity between the corrosion rates of the two studies may be due to the same influencing effect velocity had on corrosion in aerating each water.

- Comparison of the in-situ studies showed Edmonton's treated water as less corrosive than Yellowknife's treated water.

- Edmonton is, by no means, experiencing the corrosion problems as is the City of Yellowknife. This attributed to the difference in each water's tendency to precipitate $CaCO_3$. Edmonton's treated water is slightly undersaturated with respect to $CaCO_3$ compared to Yellowknife's greatly undersaturated water.

16.0 Concluding Discussion and Recommendations

A corrosion study was undertaken in the City of Yellowknife, N.W.T., to assess the ductile iron corrosion problem within the water distribution system. The purpose of this investigation was to determine the severity of the corrosion problem and to recommend remedial actions. The investigation revealed that the problem is directly related to the water chemistry, the chemical treatment used and to the presence of corrosion-causing bacteria. Test results revealed chemical treatment increases the corrosivity of the supply water. In the case of ductile iron, corrosion increased by 40% from exposure to the treated water. Similarly, for copper the increase was by 65%.

Preliminary sampling showed corrosion-causing and corrosion-intensifying bacteria to be present in low concentrations in the untreated water and absent from the treated water. However, corrosion scales extracted from the distribution system, indicated very high concentrations of corrosion-causing and corrosion-intensifying bacteria. Examples of corrosion-causing microorganisms identified include heterotrophic iron, sulfate, sulfite, and thiosulfate reducing bacteria. Examples of corrosion-intensifying microorganisms identified include sulfur and iron oxidizing bacteria. The bacterial results represent an one time sampling of the distribution system, although based on the preliminary results bacteria potentially contribute to Yellowknife's corrosion problem. Additional research, however, is required to determine to what extent bacteria contribute to Yellowknife's corrosion problem.

In-situ tests results showed Yellowknife's corrosion problem to be moderate. It was determined that the service life of ductile iron is moderately reduced by exposure to the treated water, where as, for copper, the effect is minimal.

To investigate the problem of ductile iron corrosion, a laboratory study was conducted to evaluate possible corrosion inhibitors that could be added to the potable water. Based on the laboratory results, two chemical combinations were identified as most promising: sodium hexametaphosphate and the combination of lime, carbon dioxide and sodium hydroxide.

Sodium hexametaphosphate was shown to significantly reduce the initial corrosion of each metal relative to the control with chlorine. Polyphosphate was most effective at 1.0 mg/L as P and the range of 1 to 2 mg/L as P, is recommended with the lower dosage preferable.

Polyphosphate can stimulate biological growth in the distribution system which can further accelerate corrosion. Control of biological growth in the distribution system will require maintaining an adequate chlorine residual at all times.

During the initial phase of polyphosphate treatment, high dosages are used. The laboratory study showed that high dosages can soften corrosion scales which can be resuspended to contaminate the water. Obviously mechanical cleaning of the distribution system is necessary prior to using the inhibitor if such problems are to be avoided.

Phosphate is often the limiting nutrient required for algae and aquatic macrophytes. Long term discharges of phosphate enriched wastewater could eventually lead to eutrophication problems in the receiving water.

An alternative to phosphates is the combination of lime, carbon dioxide and a pH adjustment chemical. The latter can be either sodium hydroxide or sodium carbonate. In the laboratory study, sodium hydroxide was used. Although sodium hydroxide is more economical it is also more dangerous and provides little additional alkalinity as compared to sodium carbonate. For these reasons sodium carbonate is preferred as the pH adjustment chemical.

Tests showed these chemicals promoted the precipitation and establishment of $CaCO_3$ coatings which was effective in reducing corrosion of both metals. Coatings of $CaCO_3$ were observed to have formed only on the surfaces of ductile iron metal coupons. The dosages of these chemicals which provided optimum performance, corresponded to a water quality recommended for a well-conditioned water. However, the study did not provide accurate estimates for dosages of these chemicals for use in the distribution system. The chemical dosages for these chemicals, for this purpose, can vary greatly, with the stipulation the applied dosages of each chemical correspond to a water quality recommended for a well-conditioned water. Merrill and Sanks (1978) suggested that such films can be produced for waters with the following conditions:

a. The water should be oversaturated with $CaCO_3$ and the oversaturation should be in the range of 4 to 10 mg/L as $CaCO_3$.

b. Calcium and alkalinity values should each be at least 40 mg/L as $CaCO_3$ and more if economically feasible.

c. The ratio Alkalinity/ (Cl^- + SO_4^{2-}) should be a least 5:1.

d. The pH should be in the range 6.8 to 7.3, and;

e. The water velocity should exceed 0.6 m/s.

Some of these conditions may be achieved only at the expense of another. Conditions a, b, and c are the most important and should not be compromised. Condition d, can be preserved only when the raw water is initially high in calcium and alkalinity. To condition Yellowknife's supply water to within the optimum pH range requires excessive additions of alkalinity making condition d impractical for Yellowknife.

Based on both the literature reviewed and the laboratory results it is possible to achieve a corrosion rate reduction of 20% or more for ductile iron and 50% or more for copper using the above inhibitors. In addition, the inhibitory chemical can be as a supplement to a new protective pipe lining which would serve to further reduce the corrosion rates.

These conditioning chemicals, however, may cause problems for two reasons. First, they may be dosed incorrectly. Second, the water may deposit a thin protective scale in the distribution system at a temperature of 5 °C, but form excessive scaling in hot water systems. As a result, boilers or customer's hot water heaters may have to be descaled or replaced sooner than expected.

Recommendations from the study favour using lime, carbon dioxide and sodium carbonate rather than the polyphosphate. Both chemical treatments cause the precipitation of an insoluble metal salt, to form a protective coating on the pipe's surface. However, there are potentially fewer problems associated with using the treatment with the three conditioning chemicals. Perhaps more important, using the three conditioning chemicals also conditions the water to reduce its corrosivity.

Conditioning Yellowknife's supply water to achieve a scaling potential with respect to $CaCO_3$ may prove too costly. Instead, additional research is needed to determine the effects on reducing corrosion of limited conditioning with the chemicals; lime, carbon dioxide, and sodium carbonate.

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WATER DISTRIBUTION CORROSION STUDY, CITY OF YELLOWKNIFE, N. W.T.
APPENDICES

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Appendices

Appendix A

Detailed Summary of the Water Quality Changes for the Polyphosphate Tests.

The following is a detailed summary of the water quality changes for each setting of the polyphosphate experiments. Detailed are the weakly changes in water quality throughout the duration of each corrosion test conducted using the inhibitor, sodium hexametaphosphate.

A.1 Experimental Schedules

A.1.1 Copper Experiments

Figures A.1.1.1, A.1.1.2, and A.1.1.3 are the experimental schedules for the removal of copper coupons exposed to different polyphosphate concentrations. Sample sets consisted of three coupons each and were removed weekly. The duration of the tests was approximately 30 days.

A.1.2 Ductile Iron Experiments

Figures A.1.2.1, A.1.2.2, and A.1.2.3 are the experimental schedules for the removal of ductile iron coupons exposed to different polyphosphate concentrations. Sample sets consisted of three coupons each and were removed weekly. The duration of the tests was approximately 30 days.

A.2 Laboratory Water Characteristics

Throughout the experiments, several water quality parameters were monitored weekly. These water parameters were measured prior to the immersion of coupons, and again when changing the water on a weekly basis. Presented, are the weekly variations in water quality for the immersion of ductile iron and copper coupons in polyphosphate treated waters.

Figure A.1.1.1
Experimental Schedule: 1 mg/L as P

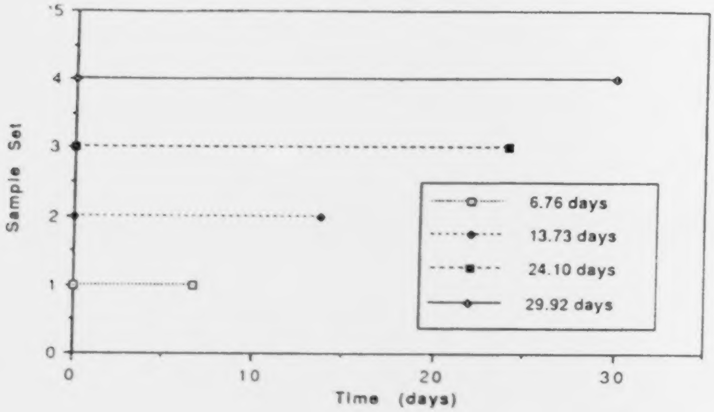


Figure A.1.1.2
Experimental Schedule: 3 mg/L as P

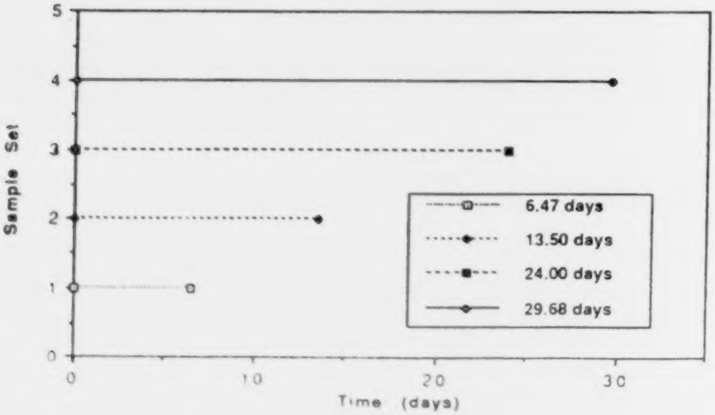


Figure A.1.1.3
Experimental Schedule: 5 mg/L as P

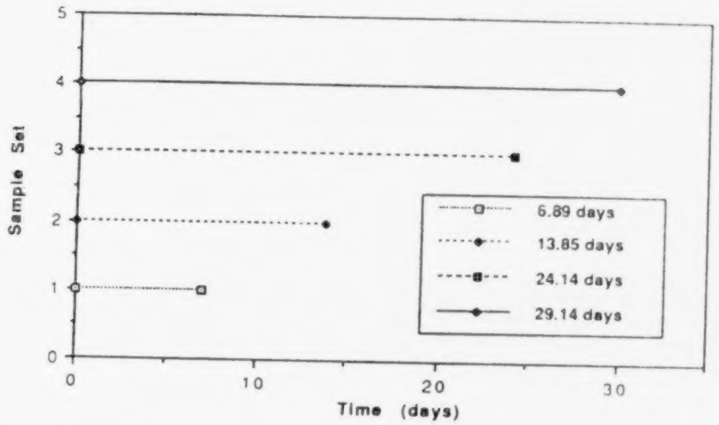


Figure A.1.2.1
Experimental Schedule: 1 mg/L as P

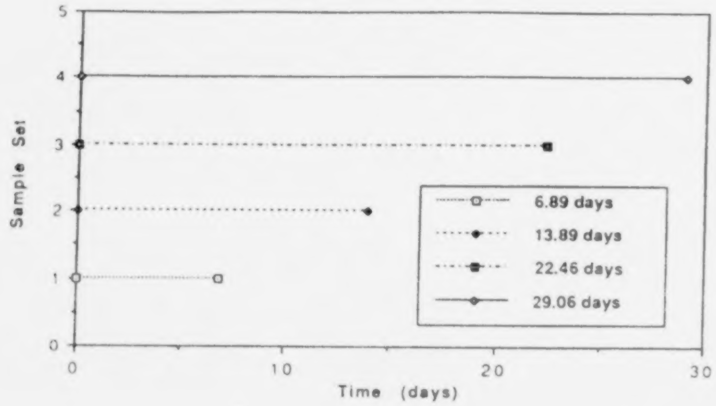


Figure A.1.2.2
Experimental Schedule: 3 mg/L as P

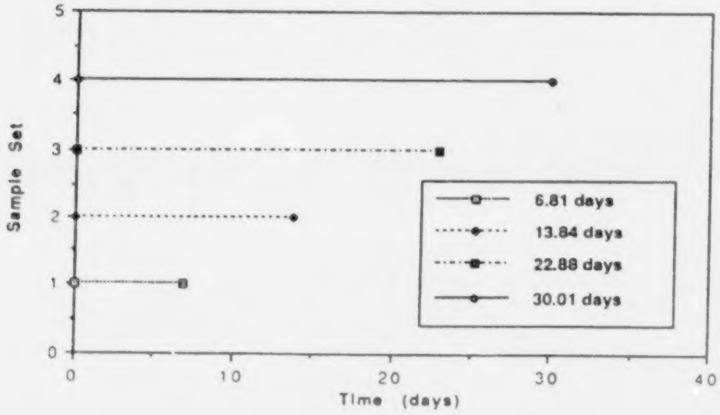
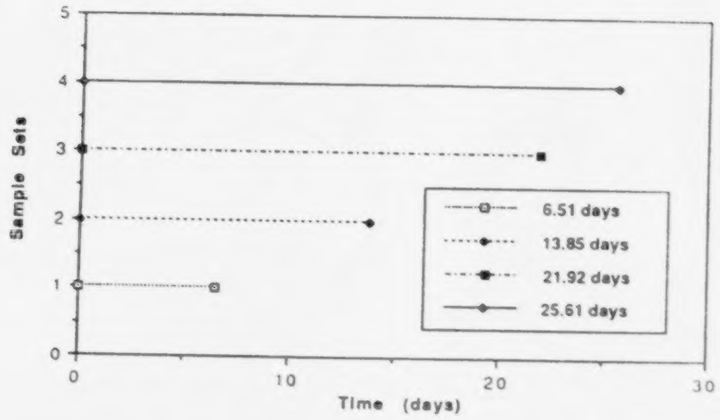


Figure A.1.2.3
Experimental Schedule: 5 mg/L as P



A.2.1 Alkalinity

A.2.1.1 Copper Experiments

Figure A.2.1.1.1 shows the weekly changes in alkalinity of the experimental waters for the immersion of copper at different polyphosphate concentrations. Shown, is that the alkalinity increased slightly for each experimental water for a weekly liquid retention time. The average increase and range by which the alkalinity changed for a weekly liquid retention time each setting was:

a. 1 mg/L P concentration: average increase was 2.7 mg/L with a range of 1.9 to 3.5 mg/L as $CaCO_3$;

b. 3 mg/L P concentration: average increase was 4.5 mg/L with a range of 3.0 to 6.0 mg/L as $CaCO_3$; and

c. 5 mg/L P concentration: average increase was 2.9 mg/L with a range of 0.3 to 4.7 mg/L as $CaCO_3$.

A.2.1.2 Ductile Iron Experiments

Figure A.2.1.2.1 shows the weekly changes in alkalinity of the experimental waters, for the immersion of ductile iron at different polyphosphate concentrations. The average increase and range by which alkalinity changed for each setting for a weekly retention time was:

a. 1 mg/L P concentration: average increase was 4.5 mg/L with a range of 3.9 to 5.1 mg/L as $CaCO_3$;

b. 3 mg/L P concentration: average increase was 5.9 mg/L with a range of 4.3 to 7.0 mg/L as $CaCO_3$; and

Figure A.2.1.1.1
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

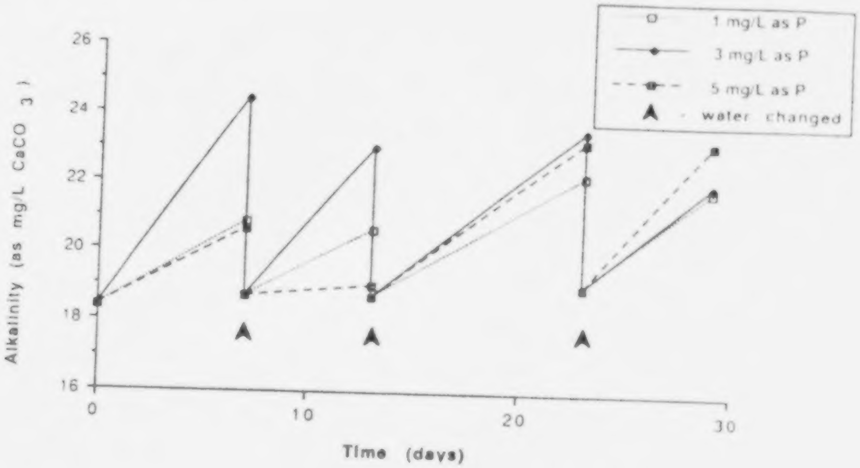
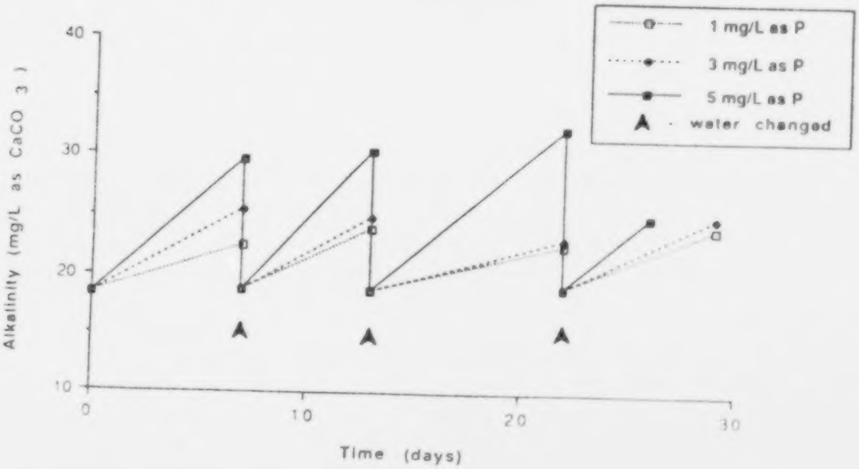


Figure A.2.1.2.1
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



c. 5 mg/L P concentration: average increase was 10.7 mg/L
with a range of 6.0 to 13.7 mg/L as $CaCO_3$.

Alkalinity increased for each of the settings for a weekly liquid retention time. Changes in alkalinity can be attributed mainly to corrosion, and to a lesser extent, chlorination. For the lower concentrations, the increases were of the same magnitude in which the corrosion rates were generally the same. However, for the higher concentration, the increases were much higher. Greater increases in alkalinity for the 5 mg/L a P, can be associated to the increased corrosion observed at this concentration.

A.2.2 Calcium

A.2.2.1 Copper Experiments

Figure A.2.2.1.1 shows the weekly changes in calcium concentration of the experimental waters, for the immersion of copper at different polyphosphate concentrations. The average increase and range by which the calcium concentration changed for a weekly liquid retention time for each setting was:

a. 1 mg/L P concentration: average increase was 0.6 mg/L
with a range of 0.2 to 0.6 mg/L as Ca^{2+};
b. 3 mg/L P concentration: average increase was 0.6 mg/L
with a range of 0.2 to 0.7 mg/L as Ca^{2+}; and
c. 5 mg/L P concentration: average increase was 0.6 mg/L
with a range of 0.5 to 0.7 mg/L as Ca^{2+}.

The calcium concentration increased for each setting, to suggest that polyphosphate had not precipitated as an insoluble metal phosphate compound onto the metal's surface. Instead, the calcium concentration of each setting increased slightly from liquid losses due to evaporation.

A.2.2.2 Ductile Iron Experiments

Figure A.2.2.2.1 shows the weekly changes in calcium concentration of the experimental waters for the immersion of ductile iron at different polyphosphate concentrations. The average decrease and range by which the calcium concentration changed for a weekly liquid retention for each setting was:

a. 1 mg/L P concentration: average change was -0.3 mg/L with a range of -0.6 to 0.1 mg/L as Ca^{2+};

b. 3 mg/L P concentration: average change was -0.7 mg/L with a range of -1.3 to -0.5 mg/L as Ca^{2+}; and

c. 5 mg/L P concentration: average change was -1.1 mg/L with a range of -1.3 to -0.8 mg/L as Ca^{2+}.

The calcium concentration of each setting decreased for a weekly liquid retention time. Shown, is the tendency for the decreases in calcium concentration to increase with increasing polyphosphate concentration.

Figure A.2.2.1.1
Weekly Changes in Calcium Concentration of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

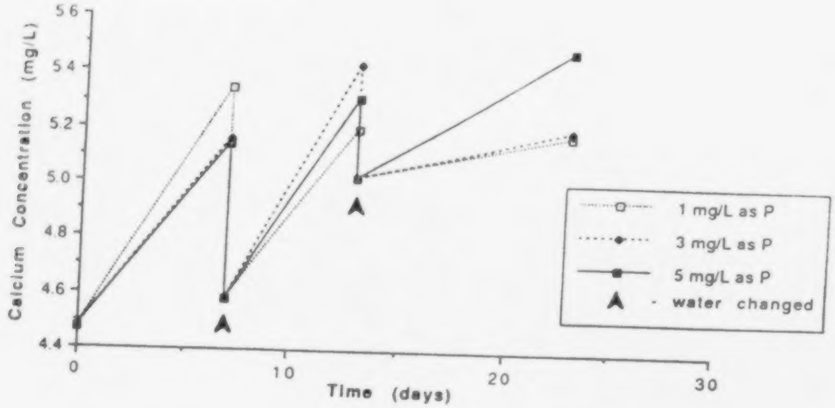
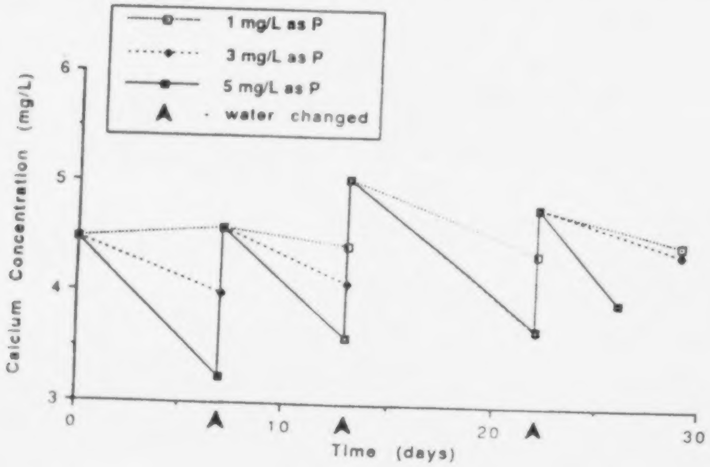


Figure A.2.2.2.1
Weekly Changes in Calcium Concentration of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



A.2.3 Chloride

A.2.3.1 Copper Experiments

Figure A.2.3.1.1 shows the weekly changes in chloride concentration of the experimental waters, for the immersion of copper at different polyphosphate concentrations. The average increase and range by which the chloride concentration changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 5.53 mg/L
with a range of 2.10 to 13.46 mg/L as Cl^-;
b. 3 mg/L P concentration: average increase was 5.04 mg/L
with a range of 3.00 to 6.59 mg/l as Cl^-; and
c. 5 mg/l P concentration: average increase was 3.51 mg/L
with a range of 2.50 to 5.08 mg/L as Cl^-.

The increases are the result of chlorination. In general, the magnitude of the increases was similar for each of the settings. Not known however, is what the chloride concentration was immediately after chlorinating the water.

A.2.3.2 Ductile Iron Experiments

Figure A.2.3.2.1 shows the weekly changes in chloride concentration of the experimental waters for the immersion of ductile iron at different polyphosphate concentrations. The average increase and range by which the chloride concentration changed for each setting for a weekly liquid retention time was:

Figure A.2.3.1.1
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

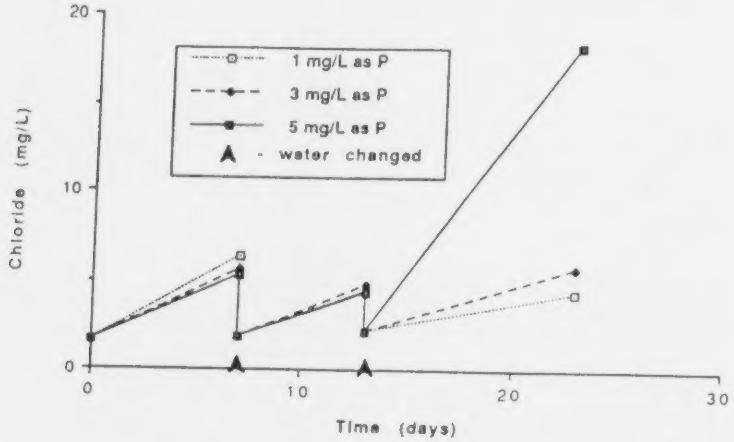
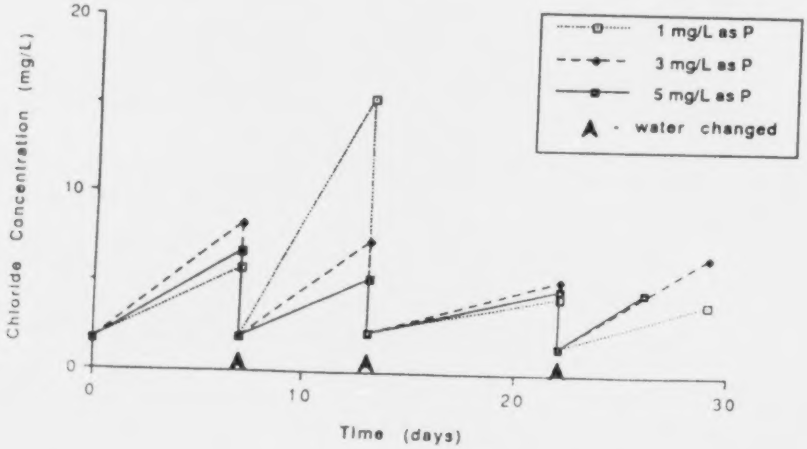


Figure A.2.3.2.1
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



a. 1 mg/L P concentration: average increase was 3.00 mg/L with a range of 2.03 to 4.64 mg/L as Cl^-;

b. 3 mg/L P concentration: average increase was 3.48 mg/L with a range of 2.90 to 4.06 mg/L as Cl^-; and

c. 5 mg/L P concentration: average increase was 7.06 mg/L with a range of 2.32 to 15.37 mg/L as Cl^-.

The chloride concentration of the experimental waters increased slightly from chlorination.

Chloride is the major aggressive ion, where the corrosion of most metals used to transport water is concerned. Larson (1970) developed the Larson's Ratio (LR) based on the relative corrosive behavior of chloride ions and the protective properties of bicarbonates.

$$LR = [Cl^-]/[HCO_3^-] \qquad \text{(units: meq/L)}$$

Observations of corrosion in waters of different quality showed the rate of corrosion of mild steel to increase significantly, if the LR value was greater than 0.2. The LR value of the raw water was calculated to vary between the range of 0.15 to 0.19 to indicate chloride, for the little alkalinity present, will not significantly influence the corrosion of ferrous metals. However, from chlorination, the LR value will have increased to above 0.2 for each setting, to potentially increase the water corrosivity.

A.2.4 Copper Concentration

A.2.4.1 Copper Experiments

Figure A.2.4.1.1 shows the weekly changes in copper concentration for the immersion of copper at different polyphosphate concentrations. The average increase and range by which the copper concentration changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 0.66 mg/L with a range of 0.56 to 0.73 mg/L as Cu^{2+};

b. 3 mg/L P concentration: average increase was 1.14 mg/L with a range of 0.87 to 1.48 mg/L as Cu^{2+}; and

c. 5 mg/L P concentration: average increase was 1.37 mg/L with a range of 1.09 to 1.42 mg/L as Cu^{2+}.

The tendency, is for copper concentration to increase with increasing polyphosphate concentration. However, analysis of the corrosion rate data shows, there is little difference between settings. The differences then, may be attributed to the differences in total surface area of the copper coupons for each setting.

A.2.5.Dissolved Oxygen Concentration

A.2.5.1.Copper Experiments

Figure A.2.5.1.1 shows the dissolved oxygen concentrations, as measured, when changing the experimental waters on a weekly basis, for the immersion of copper at different polyphosphate concentrations. The dissolved oxygen concentrations of the experimental waters were kept

Figure A.2.4.1.1
Weekly Changes in Copper Concentration of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

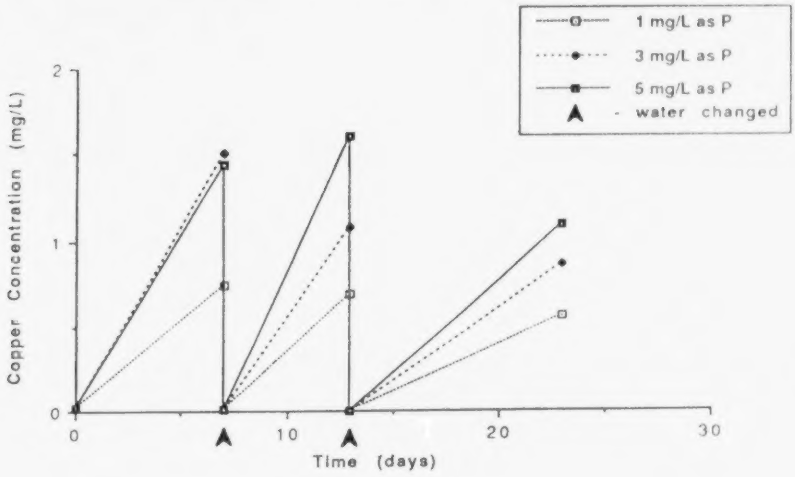


Figure A.2.5.1.1
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

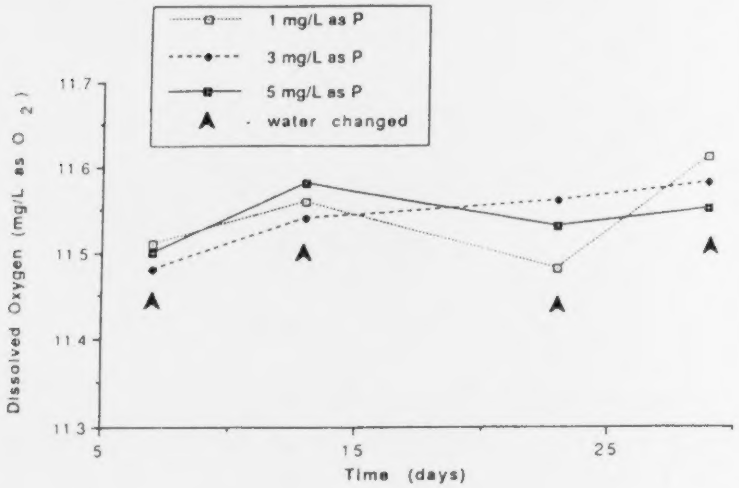
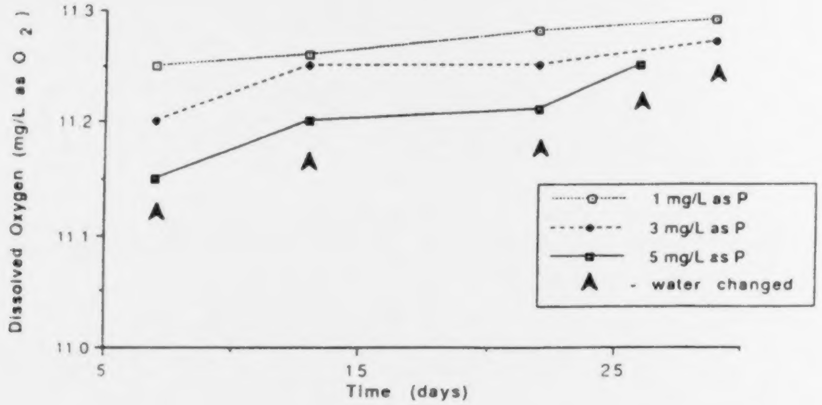


Figure A.2.5.2.1
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



relatively constant by continual aeration. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. 1 mg/L P concentration: average was 11.54 mg/L with a range of 11.48 to 11.61 mg/L as O_2;

b. 3 mg/L P concentration: average was 11.54 mg/L with a range of 11.48 to 11.58 mg/L as O_2; and

c. 5 mg/L P concentration: average was 11.54 mg/L with a range of 11.50 to 11.58 mg/L as O_2.

A.2.5.2 Ductile Iron Experiments

Figure A.2.5.2.1 shows the dissolved oxygen concentrations, as measured, when changing the experimental waters on a weekly basis, for the immersion of ductile iron at different polyphosphate concentrations. The dissolved oxygen concentrations of the experimental waters were kept relatively constant by continual aeration. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. 1 mg/L P concentration: average was 11.27 mg/L with a range of 11.25 to 11.29 mg/L as O_2;

b. 3 mg/L P concentration: average was 11.24 mg/L with a range of 11.20 to 11.27 mg/L as O_2; and

c. 5 mg/L P concentration: average was 11.20 mg/L with a range of 11.15 to 11.25 mg/L as O_2.

A.2.6. Electrical Conductivity

A.2.6.1 Copper Experiments

Figure A.2.6.1.1 shows the weekly changes in electrical conductivity of the experimental waters, for the immersion of copper at different polyphosphate concentrations. As expected, electrical conductivity increased for the experimental waters from adding sodium hexametaphosphate, chlorination, and from copper corrosion. The average increase and range by which the electrical conductivity changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 18.0 with a range of 14.0 to 21.0 umhos/cm;
b. 3 mg/L P concentration: average increase was 17.0 with a range of 14.0 to 21.0 umhos/cm; and
c. 5 mg/L P concentration: average increase was 19.0 with a range of 16.0 to 24.0 umhos/cm.

A.2.6.2 Ductile Iron Experiments

Figure A.2.6.2.1 shows the weekly changes in electrical conductivity of the experimental waters, for the immersion of ductile iron at different polyphosphate concentrations. The average increase and range by which the electrical conductivity changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 15.0 with a range of 10.0 to 17.0 umhos/cm;

Figure A.2.6.1.1
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

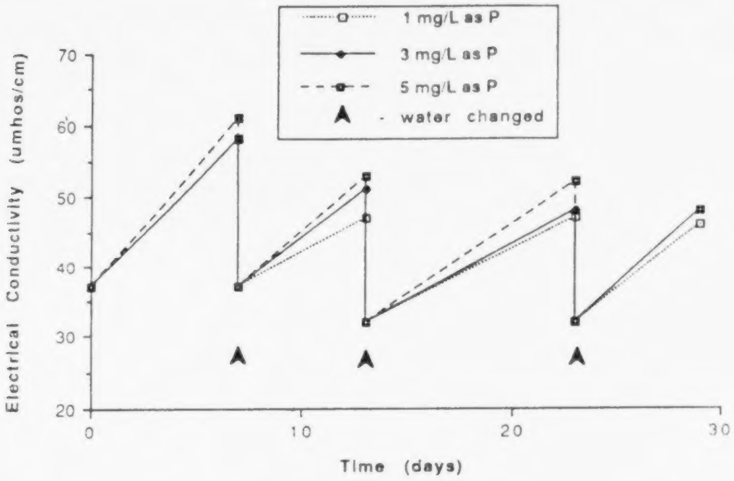
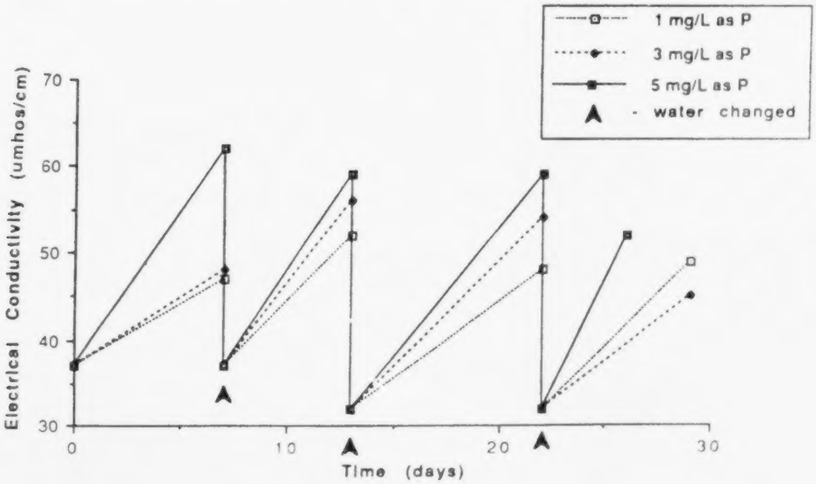


Figure A.2.6.2.1
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



b. 3 mg/L P concentration: average increase was 16.0 with a range of 11.0 to 22.0 umhos/cm; and

c. 5 mg/L P concentration: average increase was 24.0 with a range of 20.0 to 27.0 umhos/cm.

The increases were similar in magnitude to the copper results.

A.2.7 Magnesium Concentration

A.2.7.1 Copper Experiments

Figure A.2.7.1.1.shows the weekly changes in magnesium concentration of the experimental waters, for the immersion of copper at different polyphosphate concentrations. The average increase and range by which the magnesium concentration changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 0.07 mg/L with a range of 0.01 to 0.15 mg/L as Mg^{2+};

b. 3 mg/L P concentration: average increase was 0.14 mg/L with a range of 0.03 to 0.29 mg/L as Mg^{2+}; and

c. 5 mg/L P concentration: average increase was 0.15 mg/L with a range of 0.11 to 0.21 mg/L as Mg^{2+}.

The magnesium concentration of each setting increased slightly, from liquid losses due to evaporation.

A.2.7.2 Ductile Iron Experiments

Figure A.2.7.2.1 shows the weekly changes in magnesium concentration of the experimental waters, for the immersion of ductile iron at

Figure A.2.7.1.1
Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

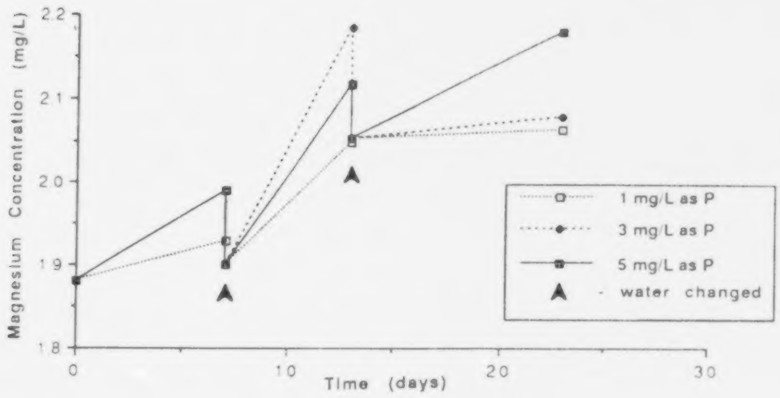
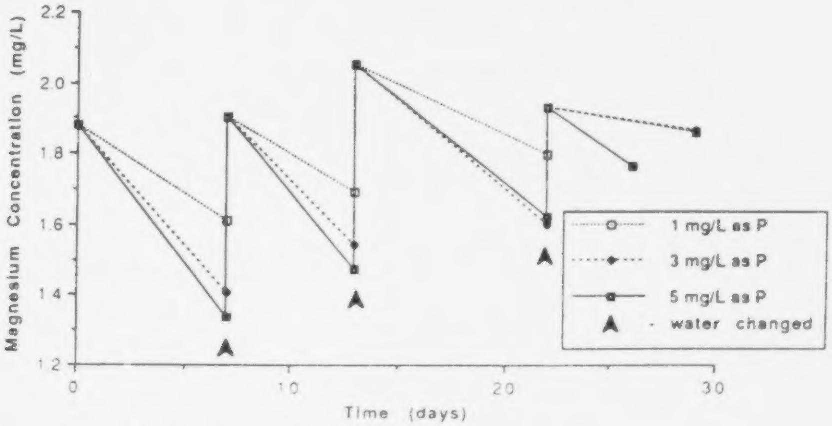


Figure A.2.7.2.1
Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



different polyphosphate concentrations. The average decrease and range by which the magnesium concentration changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average change was -0.20 mg/L with a range of -0.26 to -0.07 mg/L as Mg^{2+};

b. 3 mg/L P concentration: average change was -0.34 mg/L with a range of -0.47 to -0.07 mg/L as Mg^{2+}; and

c. 5 mg/L P concentration: average change was -0.39 mg/L with a range of -0.54 to -0.17 mg/L as Mg^{2+}.

A.2.8 Iron Concentration

A.2.8.1 Ductile Iron Experiments

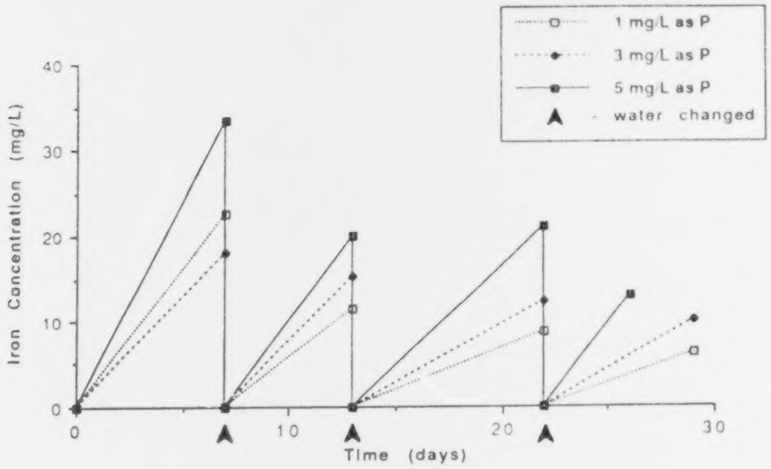
Figure A.2.8.1.1 shows the weekly changes in iron concentration of the experimental waters, for the immersion of ductile iron at different polyphosphate concentrations. The average increase and range by which the iron concentration changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 12.21 mg/L with a range of 6.07 to 22.61 mg/L as total iron;

b. 3 mg/L P concentration: average increase was 13.88 mg/L with a range of 9.91 to 18.12 mg/L as total iron; and

c. 5 mg/L P concentration: average increase was 21.80 mg/L with a range of 12.95 to 33.32 mg/L as total iron.

Figure A.2.8.1.1
Weekly Changes in Iron Concentration of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



Ductile iron corrosion is responsible for the increases in iron concentration of each setting. The tendency of the data shows the increases in iron concentration as increasing, with increasing polyphosphate concentration.

A.2.9 pH

A.2.9.1 Copper Experiments

Figure A.2.9.1.1 shows the variation in pH with time, for immersion of copper in polyphosphate treated waters. The pH of each setting remained relatively constant throughout the experiment. As well, the pH was generally the same for each experimental water. The average pH and range for each setting was:

a. 1 mg/L P concentration: average pH was 7.46 with a range of 7.40 to 7.58;
b. 3 mg/L P concentration: average pH was 7.48 with a range of 7.43 to 7.58; and
c. 5 mg/L P concentration: average pH was 7.46 with a range of 7.41 to 7.54.

Hatch (1969) suggested the optimum pH range for the use of polyphosphate, is between the pH range of 5 to 7, with deterioration of the inhibitor's performance becoming quite pronounced above pH 7.4. However, the presence of bimetallic ions can increase the effective range of inhibition to pH 7.5 to 8.0 (AWWA, 1989).

Figure A.2.9.1.1
Variations in pH With Time for the Immersion of Copper Coupons in Polyphosphate Treated Waters

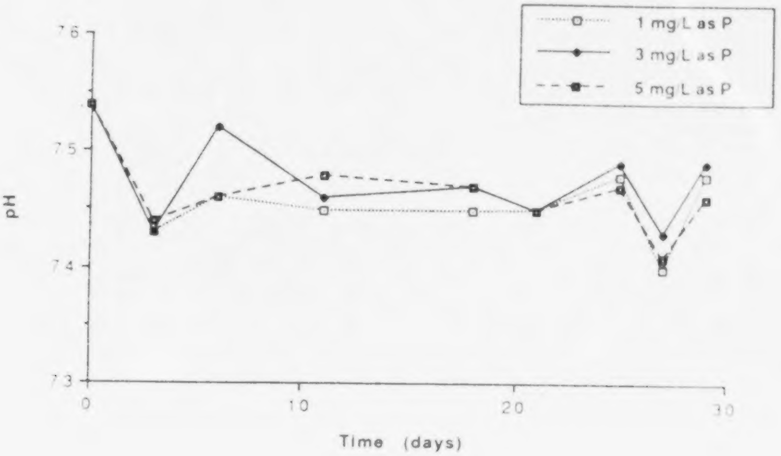
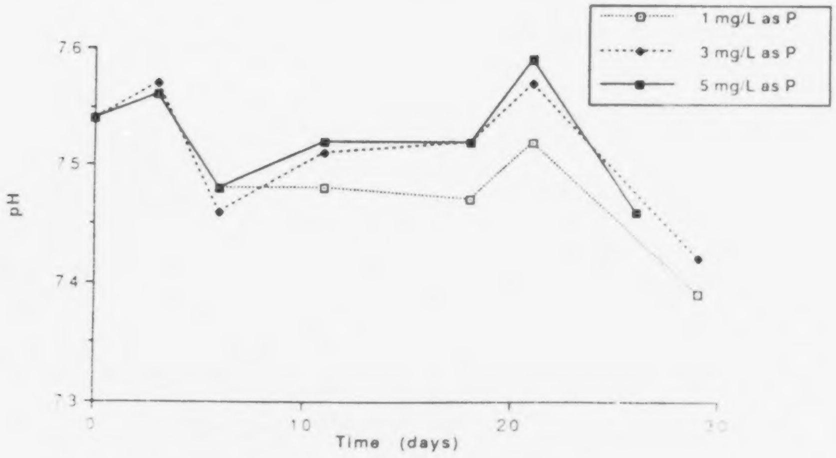


Figure A.2.9.2.1
Variations in in pH With Time for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



A.2.9.2 Ductile Iron Experiments

Figure A.2.9.2.1 shows the variation in pH with time, for immersion of ductile iron in polyphosphate treated waters. The pH of each setting remained relatively constant throughout the experiments. The average pH and range for each setting was:

a. 1 mg/L P concentration: average pH was 7.49 with a range of 7.39 to 7.56;
b. 3 mg/L P concentration: average pH was 7.51 with a range of 7.42 to 7.57; and
c. 5 mg/L P concentration: average pH was 7.52 with a range of 7.46 to 7.59.

A.2.10 Sodium Hexametaphosphate Concentration

A.2.10.1 Copper Experiments

Polyphosphate concentration was the control parameter by which the inhibitor was evaluated. Figure A.2.10.1.1 shows the daily changes in polyphosphate concentration of the experimental waters, with the immersion of copper at different concentrations. The polyphosphate concentration for each setting, remained relatively constant with time and increased slightly from to liquid losses due to evaporation. The average increase and range by which the polyphosphate concentration changed for each setting was:

a. 1 mg/L P concentration: average change was 0.1 mg/L with a range of -0.2 to 0.1 mg/L P;
b. 3 mg/L P concentration: average change was 0.2 mg/L with a range of -0.3 to 0.1 mg/L P; and

c. 5 mg/L P concentration: average change was 0.2 mg/L with a range of -0.1 to 0.2 mg/L P.

Copper's inability to generate the current necessary to deposit a polyphosphate film, can account for why the concentrations did not decrease. That is, copper, when exposed alone to polyphosphate treated waters, is not coated. However, copper is coated readily when it constitutes the cathode of a galvanic couple (AWWA, 1985). Consequently it was not necessary to monitor polyphosphate concentration on a daily basis, as it was not necessary to add polyphosphate.

Samples were also analyzed for orthophosphate concentration. The orthophosphate concentrations of samples were less than 0.1 mg/L as P, to indicate the rate of hydrolysis of polyphosphate to orthophosphate was very slow and insignificant for a weekly liquid retention time.

A.2.10.2 Ductile Iron Experiments

Figure A.2.10.2.1 shows the daily changes in polyphosphate concentration of the experimental waters, with the immersion of ductile iron. Each setting required daily chemical adjustment to replaced the polyphosphate adsorbed onto the metal surface or scale precipitate in solution. Polyphosphate consumption was initially high, and later decreased with time. The greatest magnitude in consumption, on a daily basis occurred for the polyphosphate concentration 5 mg/L as P. The average decrease and range by which the polyphosphate concentration changed for each setting was:

Figure A.2.10.1.1
Daily Fluctuations in Polyphosphate Contrations for Copper Coupons Immersed in Polyphosphate Treated Waters

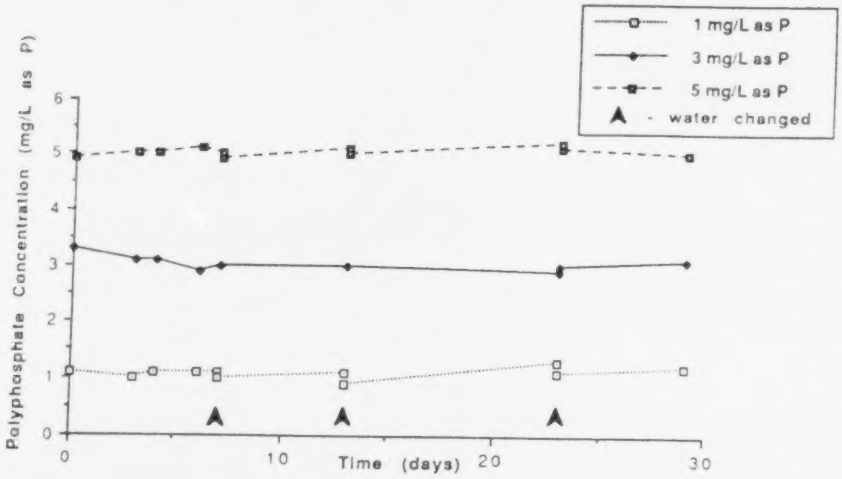
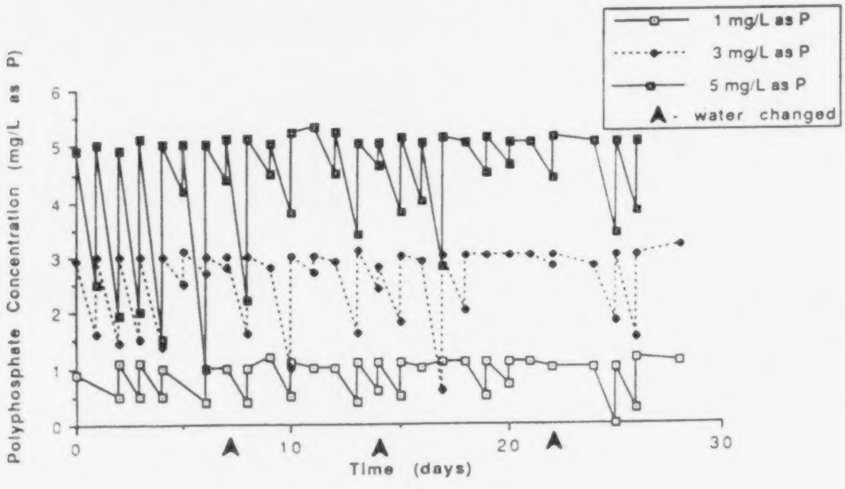


Figure A.2.10.2.1
Daily Changes in Polyphosphate Concentration of the Experimental Waters for the Immersion of Ductile Iron



a. 1 mg/L P concentration: average change was -0.3 mg/L
with a range of -1.0 to 0.2 mg/L P;
b. 3 mg/L P concentration: average change was -0.7 mg/L
with a range of -2.4 to 0.2 mg/L P; and
c. 5 mg/L P concentration: average change was -1.3 mg/L
with a range of -4.0 to -0.4 mg/L P.

The inconsistency in the magnitude by which the polyphosphate concentrations changed daily, is due to a number of factors including variable adsorption of polyphosphate on the surfaces of metal coupons, and scale precipitate in solution. As well as from the subsequent removal of coupons with time, decreasing the total surface area for the adsorption of polyphosphate.

A.2.11 Silicate Concentration

A.2.11.1 Copper Experiments

Figure A.2.11.1.1 shows the weekly changes in silicate concentration of the experimental water, for the immersion of copper at different polyphosphate concentrations. The average increase and range by which the silicate concentration changed for each setting for weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 0.08 mg/L
with a range of 0.04 to 0.15 mg/L as Si;
b. 3 mg/L P concentration: average increase was 0.12 mg/L
with a range of 0.04 to 0.25 mg/L as Si; and

c. 5 mg/L P concentration: average increase was 0.10 mg/L
with a range of 0.04 to 0.15 mg/L as Si.

The silicate concentration of each setting increased slightly from liquid losses due to evaporation.

A.2.11.2 Ductile Iron Experiments

Figure A.2.11.2.1 shows the weekly changes in silicate concentration, for the immersion of ductile iron at different polyphosphate concentrations. The average increase and range by which the silicate concentration changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 0.66 mg/L
with a range of 0.35 to 0.99 mg/L as Si;
b. 3 mg/L P concentration: average increase was 0.68 mg/L
with a range of 0.40 to 0.92 mg/L as Si; and
c. 5 mg/L P concentration: average increase was 0.91 mg/L
with a range of 0.37 to 1.31 mg/L as Si.

The magnitude by which the silicate concentration increased for each setting was dependent on the polyphosphate concentration. Shown, is that the higher the polyphosphate concentration, the greater the magnitude of the increases. Ductile iron has 2.5 % silicate as part of its elemental composition. Ductile iron corrosion was shown to increase with increasing polyphosphate concentration. Consequently, the increases in silicate concentration are attributed to ductile iron corrosion, at the different polyphosphate concentrations.

Figure A.2.11.1.1
Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

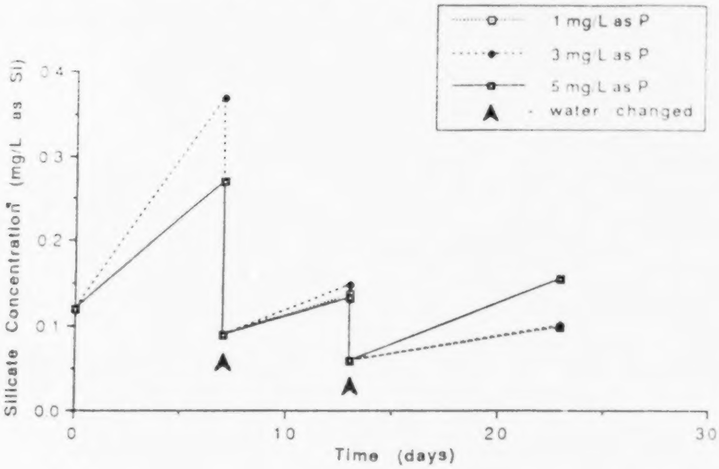
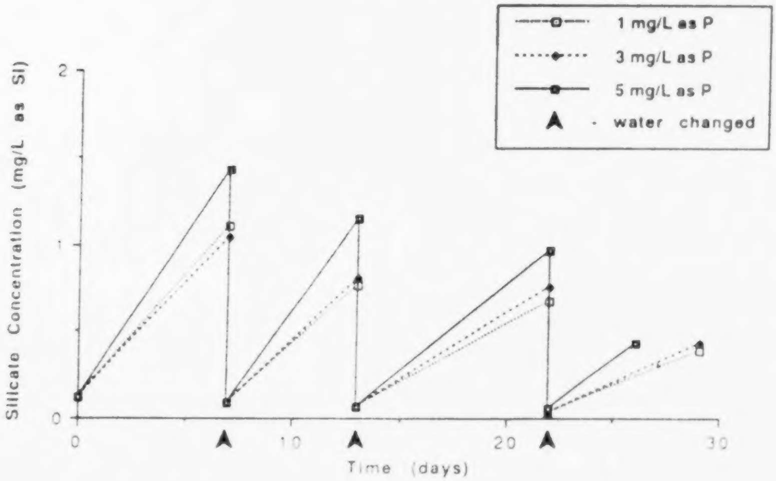


Figure A.2.11.2.1
Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



A.2.12 Sodium Concentration

A.2.12.1 Copper Experiments

Figure A.2.12.1.1 shows the weekly changes in sodium concentration, for the immersion of copper at different polyphosphate concentrations. The average increase and range by which the sodium concentration changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 2.91 mg/L with a range of 2.35 to 3.23 mg/L as Na^+;

b. 3 mg/L P concentration: average increase was 5.29 mg/L with a range of 4.73 to 5.64 mg/L as Na^+; and

c. 5 mg/L P concentration: average increase was 6.49 mg/L with a range of 5.85 to 6.96 mg/L as Na^+.

The increases in sodium concentration of each setting are proportional to the chemicals added.

A.2.12.2 Ductile Iron Experiments

Figure A.2.12.2.1 shows the weekly changes in sodium concentration, for the immersion of ductile iron at different polyphosphate concentrations. The average increase and range by which the sodium concentration changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 4.30 mg/L with a range of 3.49 to 5.54 mg/L as Na^+;

b. 3 mg/L P concentration: average increase was 8.11 mg/L with a range of 6.12 to 10.04 mg/L as Na^+; and

Figure A.2.12.1.1
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

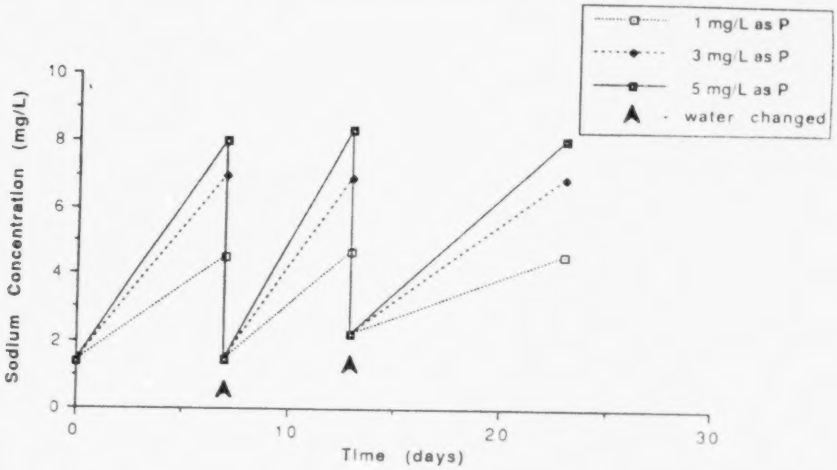
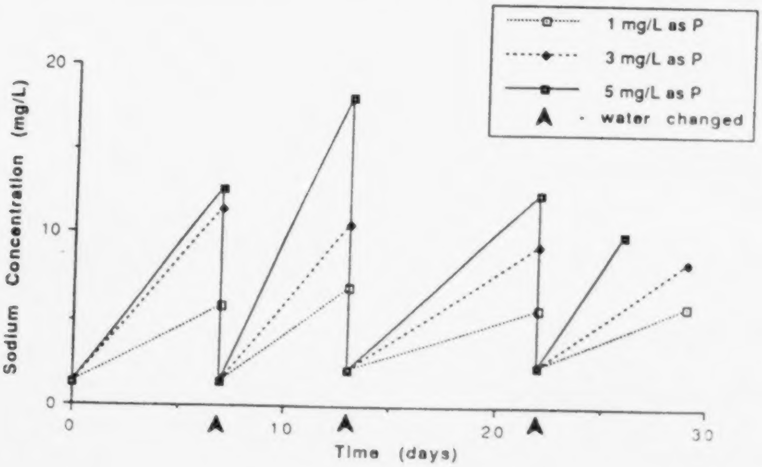


Figure A.2.12.2.1
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



c. 5 mg/L P concentration: average increase was 11.46 mg/L with a range of 7.69 to 16.74 mg/L as Na^+.

The increases in sodium concentration were from chemical addition and were higher than the copper results, due to the requirement to add more polyphosphate on a regular basis.

A.2.13 Sulfate

A.2.13.1 Copper Experiments

Figure A.2.13.1.1 shows the weekly changes in sulfate concentration of the experimental waters, for the immersion of copper at different polyphosphate concentrations. The sulfate concentration of the experimental waters decreased to a value below the analysis detection limit for a weekly exposure time. The average decrease and range by which the sulfate concentration changed for each setting for a weekly retention time was:

a. 1, 3 and 5 mg/L P concentrations: average change was -2.85 mg/L with a range of -2.71 to -2.98 mg/L as SO_4^{2-}.

A.2.13.2 Ductile Iron Experiments

Figure A.2.13.2.1 shows the weekly changes in sulfate concentration of the experimental waters, for the immersion of ductile iron at different polyphosphate concentrations. The average decrease and range by which the sulfate concentration changed for each setting for a weekly retention time was:

a. 1 mg/L P concentration: average change was -1.66 mg/L with a range of -2.33 to -0.83 mg/L as SO_4^{2-};

Figure A.2.13.1.1
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

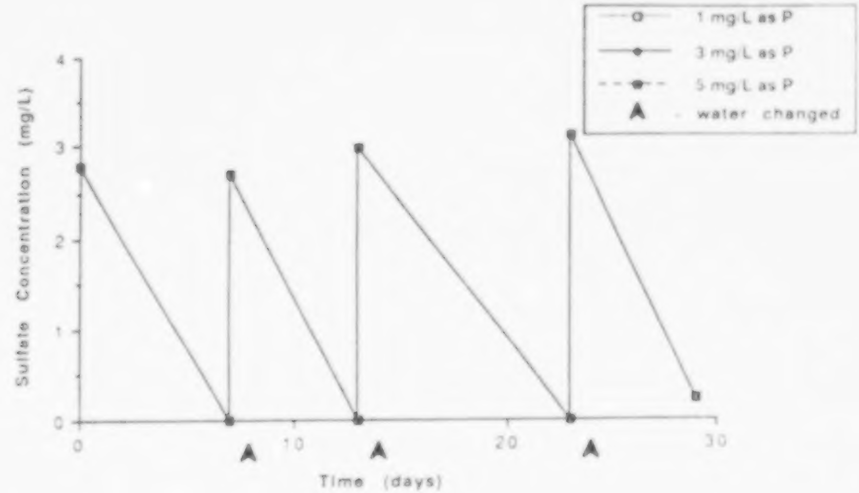
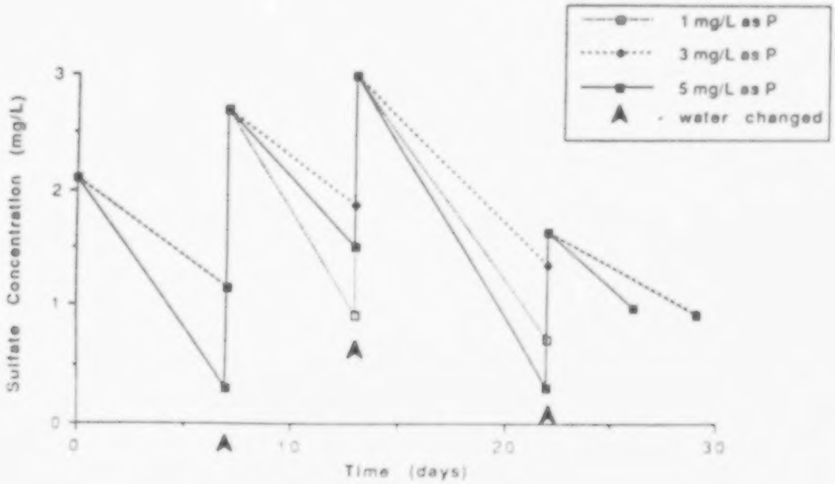


Figure A.2.13.2.1
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



b. 3 mg/L P concentration: average change was -1.02 mg/L with a range of -1.54 to -0.83 mg/L as SO_4^{2-}; and

c. 5 mg/L P concentration: average change was -1.58 mg/L with a range of -2.66 to -0.74 mg/L as SO_4^{2-}.

A.2.14 Temperature

The temperature at which the experiments were performed, ranged from 5 to 7 °C.

A.2.15 Total Hardness Concentration

A.2.15.1 Copper Experiments

Figure A.2.15.1.1 shows the weekly changes in total hardness concentration of the experimental waters, for the immersion of copper at different polyphosphate concentrations. The total hardness concentrations changed very little between the initial and final concentration of the experimental waters for a weekly liquid retention time. The average increase and range by which the total hardness changed for each setting during a weekly liquid retention time was:

a. 1 mg/L P concentration: average change was -0.2 mg/L with a range of -0.4 to 0.2 mg/L as $CaCO_3$;

b. 3 mg/L P concentration: average change was zero with a range of -0.6 to 0.4 mg/L as $CaCO_3$; and

c. 5 mg/L P concentration: average increase was +0.2 mg/L with a range of -1.4 to 1.4 mg/L as $CaCO_3$.

The little change in total hardness concentration supports the previous suggestion, that polyphosphate had not precipitated as an insoluble salt of hardness causing cations on the surfaces of copper coupons.

A.2.15.2 Ductile Iron Experiments

Figure A.2.15.2.1 shows the weekly changes in total hardness concentration of the experimental waters for the immersion of ductile iron at different polyphosphate concentrations. Polyphosphate complexes with divalent cations and is precipitated as an insoluble metal phosphate compound on the metal's surface to reduce the water's hardness. The results supported this concept. Figure A.2.15.2.1 shows the total hardness concentration decreasing, with increasing polyphosphate concentration. As well, the magnitude by which hardness concentrations decreased, lessened with increased contact time, due to the removal of coupons. The average decrease and range by which the total hardness changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average change was -0.4 mg/L with a range of -3.0 to 1.4 mg/L as $CaCO_3$;

b. 3 mg/L P concentration: average change was -3.1 with a range of -4.0 to -2.0 to mg/L as $CaCO_3$; and

c. 5 mg/L P concentration: average change was -4.9 with a range of -8.0 to -3.1 mg/L as $CaCO_3$.

Figure A.2.15.1.1

Weekly Changes in Total Hardness Concentration of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

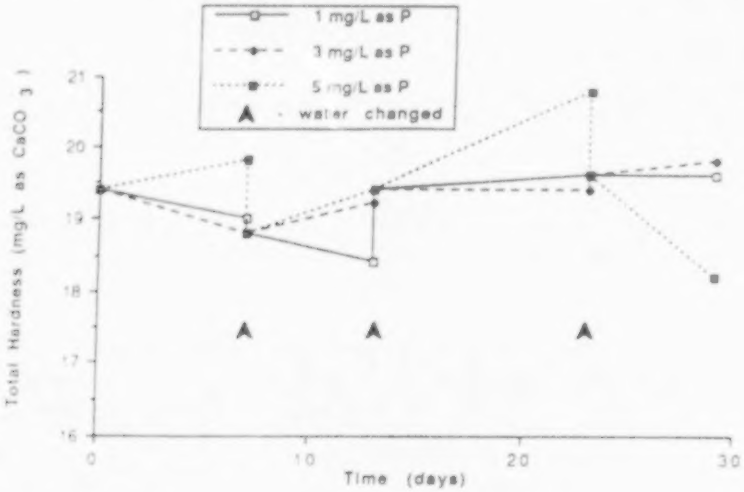
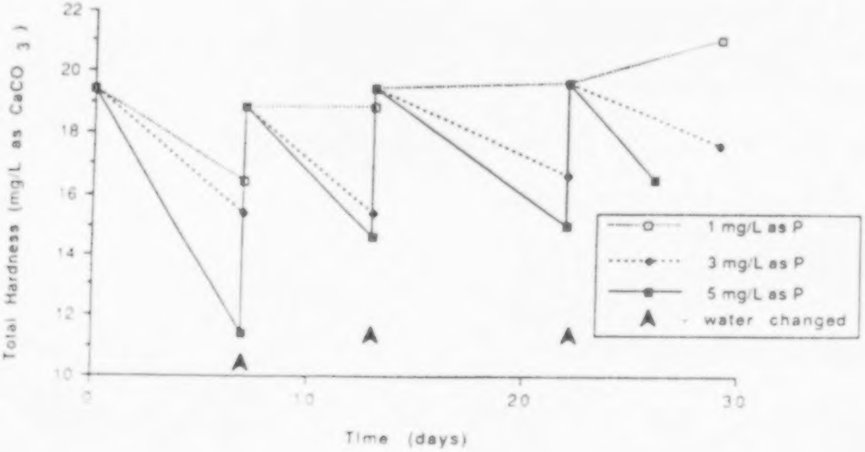


Figure A.2.15.2.1

Weekly Changes in Total Hardness Concentration of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



A.2.16 Turbidity

A.2.16.1 Copper Experiments

Figure A.2.16.1.1 shows the weekly changes in turbidity of the experimental waters, for the immersion of copper at different polyphosphate concentrations. The average increase and range by which turbidity changed for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 0.5 with a range of 0.0 to 1.0 NTU;
b. 3 mg/L P concentration: average increase was 0.8 with a range of 0.5 to 1.1 NTU; and
c. 5 mg/L P concentration: average increase was 0.8 with a range of 0.3 to 1.4 NTU.

The increases in turbidity are attributed to both copper corrosion and chemical additions. The increases for each setting were generally the same.

A.2.16.2 Ductile Iron Experiments

Figure A.2.16.2.1 shows the weekly changes in turbidity of the experimental waters for the immersion of ductile iron at different polyphosphate concentrations. Hatch and Rice (1939) reported that polyphosphate is adsorbed onto surfaces of old metal salts or oxides. However, high polyphosphate concentrations causes a softening of corrosion scales which, from turbulent conditions inside the pipe, can be resuspended to greatly increase the water's turbidity. This was observed to occur for each of the polyphosphate concentrations, with the problem becoming more severe with the higher concentrations. However, the magnitude by which turbidity

Figure A.2.16.1.1
Weekly Changes in Turbidity of the Experimental Waters for the Immersion of Copper Coupons in Polyphosphate Treated Waters

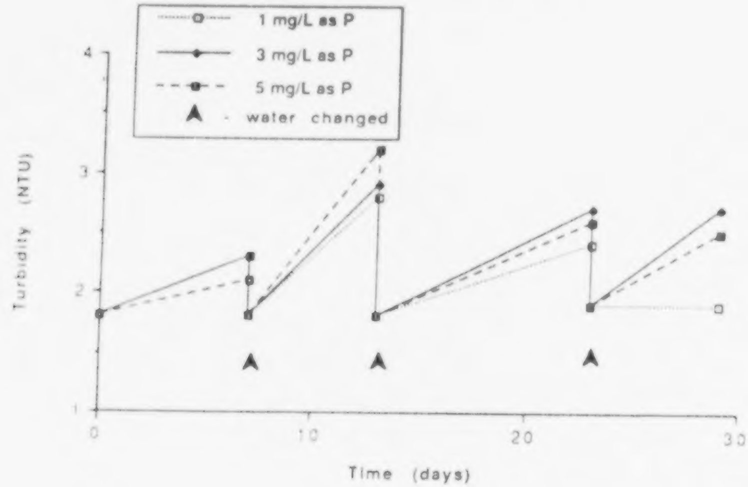
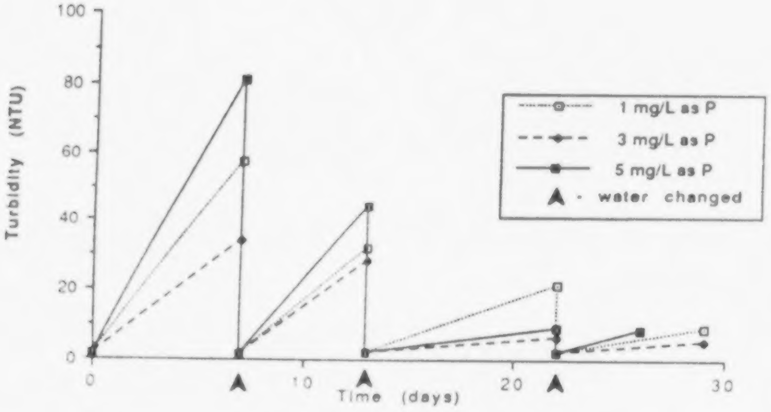


Figure A.2.16.2.1
Weekly Changes in Turbidity of the Experimental Waters for the Immersion of Ductile Iron Coupons in Polyphosphate Treated Waters



increased lessened with increased exposure time, due to the removal of coupons. The average increase and range by which the turbidity increased for each setting for a weekly liquid retention time was:

a. 1 mg/L P concentration: average increase was 28.0 with a range from 7.3 to 55.2 NTU;

b. 3 mg/L P concentration: average increase was 16.5 with a range from 3.4 to 32.2 NTU; and

c. 5 mg/L P concentration: average increase was 33.7 with a range from 6.4 to 79.2 NTU.

Appendix B

Detailed Summary of the Water Quality Changes for the Sodium Carbonate Tests.

The following is a detailed summary of the water quality changes for each setting of the sodium carbonate experiments. Detailed are the weakly changes in water quality throughout the duration of each corrosion test conducted using the inhibitor, sodium carbonate.

B.1 Experimental Schedule

B.1.1 Copper Experiments

Figures B.1.1.1, B.1.1.2, and B.1.1.3 are the experimental schedules for the removal of copper coupons exposed to different pH settings. Sample sets consisted of two to four coupons and sets were removed weekly. The duration of the experiments was approximately 36 days.

B.1.2 Ductile Iron Experiments

Figures B.1.2.1, B.1.2.2, and B.1.2.3 are the experimental schedules for the removal of ductile iron coupons exposed to different pH settings. Sample sets consisted of two coupons and sets were removed weekly. The duration of experiments was approximately 28 days.

B.2 Laboratory Water Characteristics

Throughout the experiments, several water quality parameters were monitored on a weekly basis. These water parameters were measured prior to the immersion of coupons, and again when changing the water on a weekly basis. Presented, are the weekly variations in water quality for the immersion of ductile iron and copper coupons at different pH settings.

Figure B.1.1.1
Experimental Schedule: pH 7.5, NaCO3

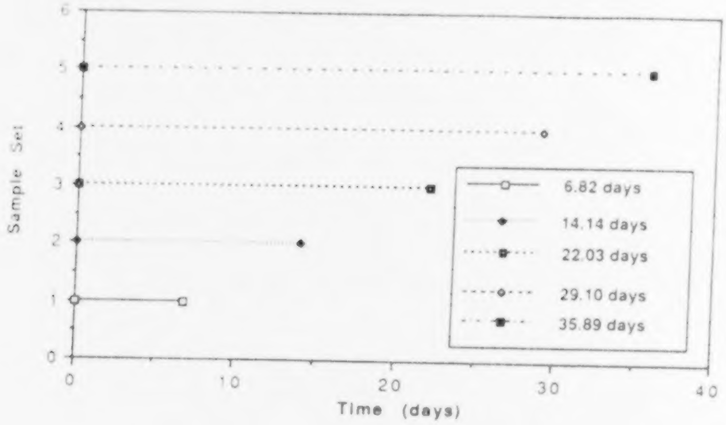


Figure B.1.1.2
Experimental Schedule: pH 8.0, NaCO3

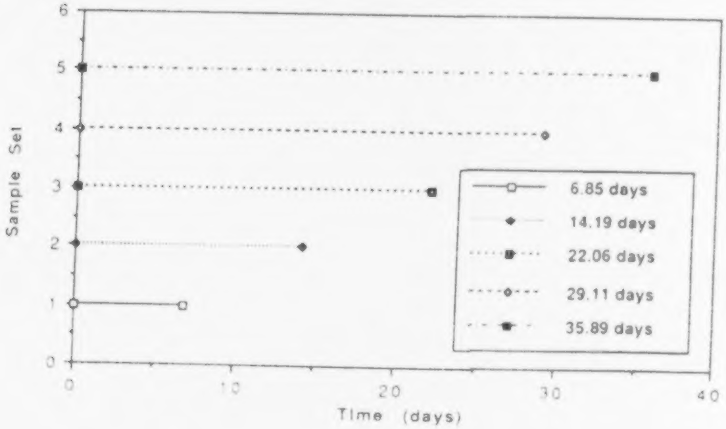


Figure B.1.1.3
Experimental Schedule: pH 8.5, $NaCO_3$

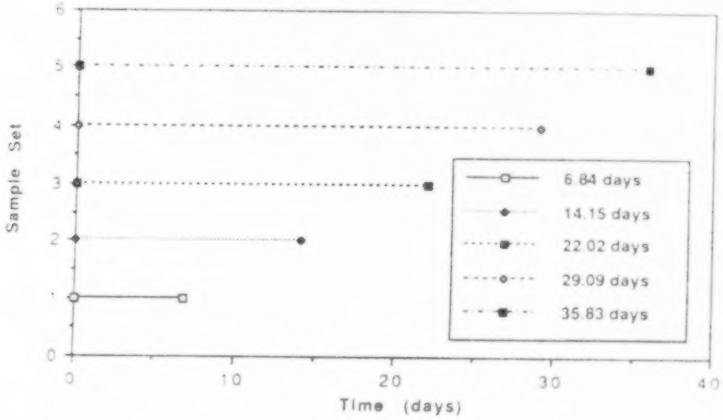


Figure B.1.2.1
Experimental Schedule: pH 7.5, NaCO3

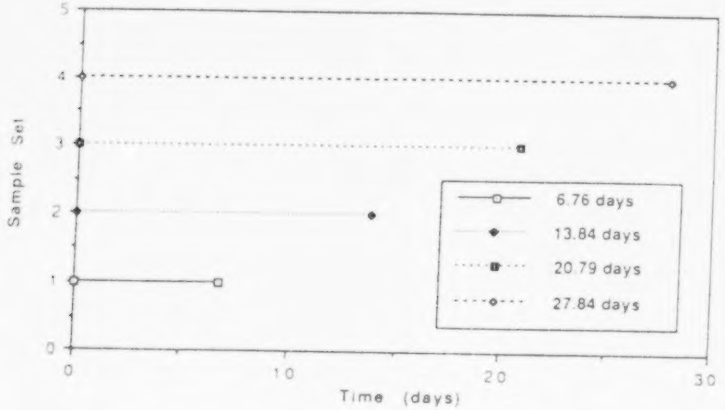


Figure B.1.2.2
Experimental Schedule: pH 8.0, NaCO3

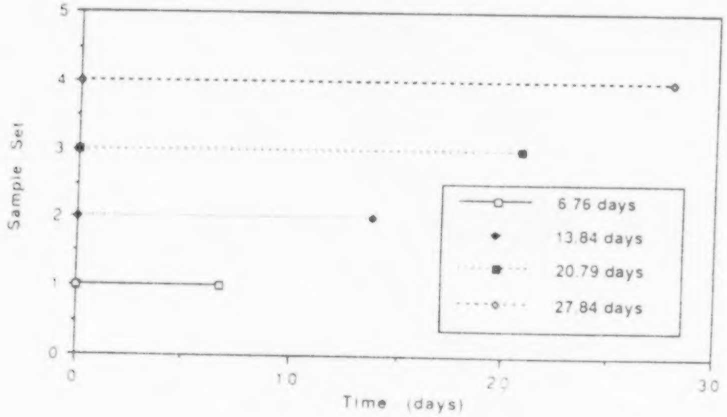
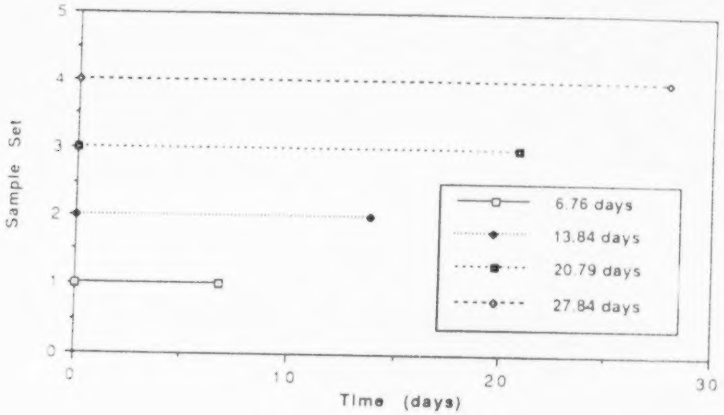


Figure B.1.2.3
Experimental Schedule: pH 8.5, NaCO3



B.2.1 Alkalinity

B.2.1.1 Copper Experiments

Figure B.2.1.1.1 shows the weekly changes in alkalinity of the experimental waters from the continual addition of sodium carbonate, to maintain the desired pH settings. The average increase and range by which the alkalinity changed for each pH setting for a weekly retention time was:

a. pH 7.5: the average increase was 14.2 mg/L with a range of 10.0 to 22.6 mg/L as $CaCO_3$;

b. pH 8.0: the average increase was 52.3 mg/L with a range of 36.8 to 77.8 mg/L as $CaCO_3$; and

c. pH 8.5: the average increase was 123.9 mg/L with a range of 113.4 to 144.0 mg/L as $CaCO_3$.

The increases in alkalinities were slightly higher than those increases observed for copper using sodium hydroxide. Increasing the pH, alkalinity, and electrical conductivity was beneficial in reducing copper corrosion, as previously discussed.

B.2.1.2 Ductile Iron Experiments

Figure B.2.1.2.1 shows the weekly changes in alkalinity of the experimental waters, for the immersion of ductile iron at different pH settings. The average increase and range by which the alkalinity changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: the average increase was 113.1 mg/L with a range of 102.4 to 120.0 mg/L as $CaCO_3$;

b. pH 8.0: the average increase was 247.5 mg/L with a range of 231.8 to 256.4 mg/L as $CaCO_3$; and

c. pH 8.5: the average increase was 534.4 mg/L with a range of 504.6 to 557.8 mg/L as $CaCO_3$.

The increases in alkalinity of each setting were primarily from the sodium hydroxide addition to maintain the desired pH settings. These increases were greater than for the copper experiments. This is attributed to the differences in corrosion rates of each metal type. The fast rusting of ductile iron would have consumed more alkalinity than the slow tarnishing of copper for scale formation, requiring the addition of more sodium carbonate on a periodic basis for the ductile iron experiments.

B.2.2 Calcium Concentration

B.2.2.1 Copper Experiments

Figure B.2.2.1.1 shows the weekly changes in calcium concentration of the experimental waters, for the immersion of copper at the different pH settings. The average increase and range by which the calcium concentration changed for each pH setting for a weekly retention time was:

a. pH 7.5: average increase was 0.7 mg/L with a range of 0.6 to 1.1 mg/L as Ca^{2+};

b. pH 8.0: average increase was 0.6 mg/L with a range of 0.2 to 0.9 mg/L as Ca^{2+}; and

c. pH 8.5: average change was -0.3 mg/L with a range of -0.6 to -0.1 mg/L as Ca^{2+}.

Figure B.2.1.1.1
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Copper At Different pH Settings

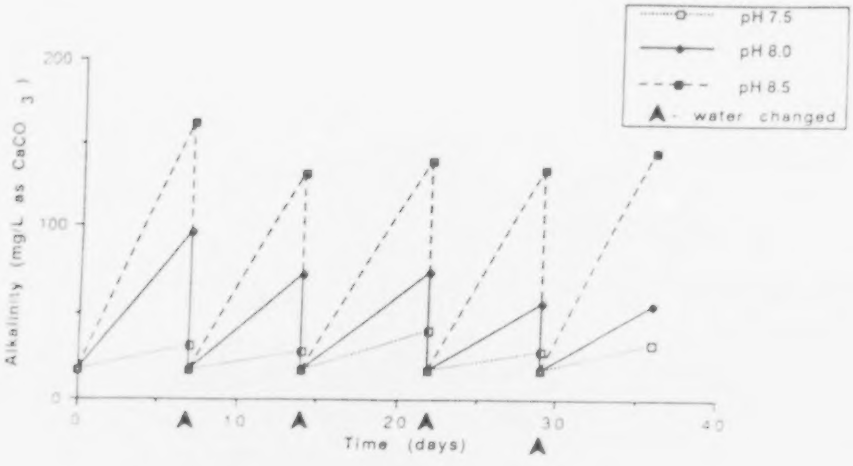
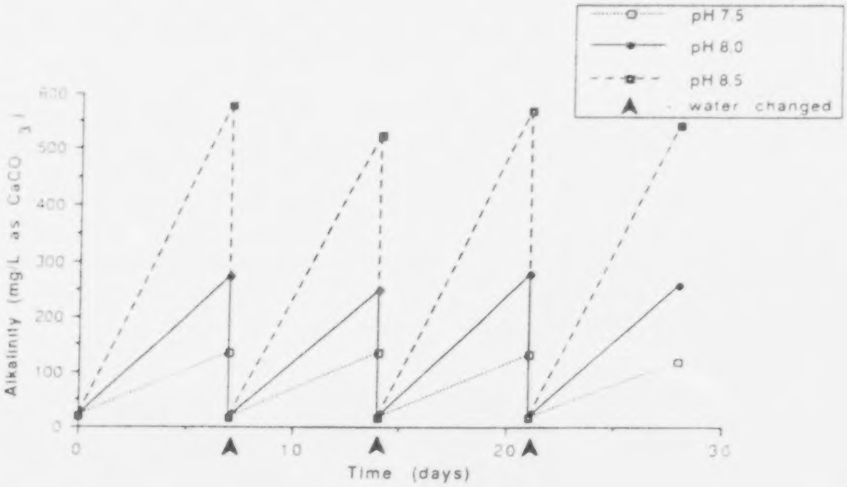


Figure B.2.1.2.1
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



The calcium concentrations increased slightly from liquid losses due to evaporation.

B.2.2.2 Ductile Iron Experiments

Figure B.2.2.2.1 shows the weekly changes in calcium concentration of the experimental waters, for the immersion of ductile iron at different pH settings. Opposite to the copper results, is the calcium concentrations decreased for a weekly liquid retention time. Calcium carbonate will deposit on the surfaces of ductile iron when exposed alone in waters that are slightly undersaturated with respect to $CaCO_3$ due to local increases in pH at the metal's surface, which is caused by corrosion. The average decrease and range by which the calcium concentration changed for each pH setting for a weekly retention time was:

a. pH 7.5: average change was -0.5 mg/L with a range of
-0.5 to -0.3 mg/L as Ca^{2+};
b. pH 8.0: average change was -0.9 mg/L with a range of
-1.3 to -0.2 mg/L as Ca^{2+}; and
c. pH 8.5: average change was -1.5 mg/L with a range of
-2.5 to -0.7 mg/L as Ca^{2+}.

The tendency of the data shows the decreases in calcium concentration as increasing with increasing pH.

Figure B.2.2.1.1
Weekly Changes in Calcium Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

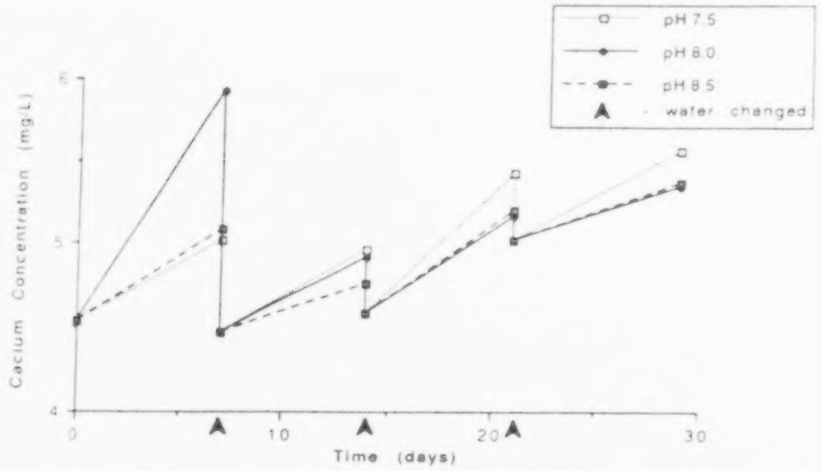
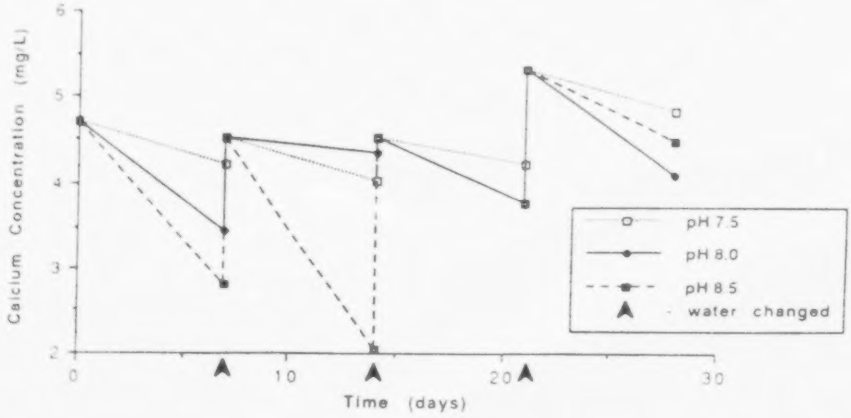


Figure B.2.2.2.1
Weekly Changes in Calcium Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



B.2.3 Chloride Concentration

B.2.3.1 Copper Experiments

Figure B.2.3.1.1 shows the weekly changes in chloride concentration of the experimental waters, for the immersion of copper at different pH settings. The average increase and range by which the chloride concentration changed for each pH setting for a weekly retention time was:

a. pH 7.5: the average increase was 3.51 mg/L with a range of 3.32 to 3.81 mg/L as Cl^-;

b. pH 8.0: the average increase was 4.03 mg/L with a range of 3.02 to 6.00 mg/L as Cl^-; and

c. pH 8.5: the average increase was 3.50 mg/L with a range of 2.91 to 4.33 mg/L as Cl^-.

B.2.3.2 Ductile Iron Experiments

Figure B.2.3.2.1 shows the weekly changes in chloride concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The chloride concentrations increased from chlorination. As discussed previously, is chlorine is the major aggressive ion for increasing the corrosion of steel and ferrous metals. However, in addition to the increases in the chloride concentrations, the alkalinity of each water also increased to reduce chloride's effect for influencing corrosion. The average increase and range by which the chloride concentration changed for each pH setting for a weekly retention time was:

Figure B.2.3.1.1
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

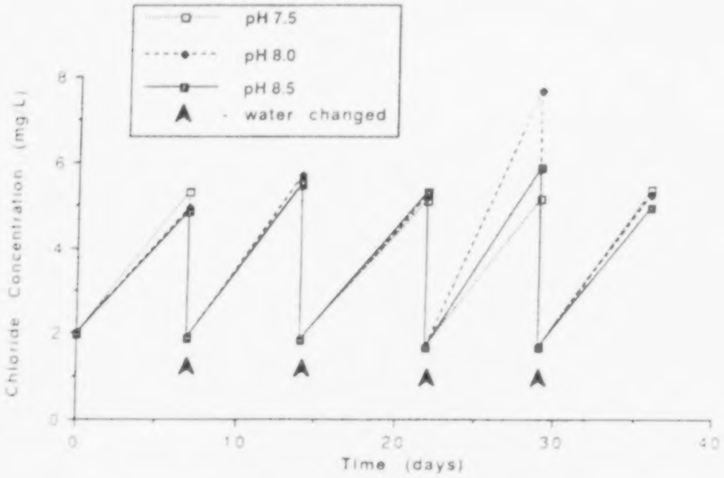
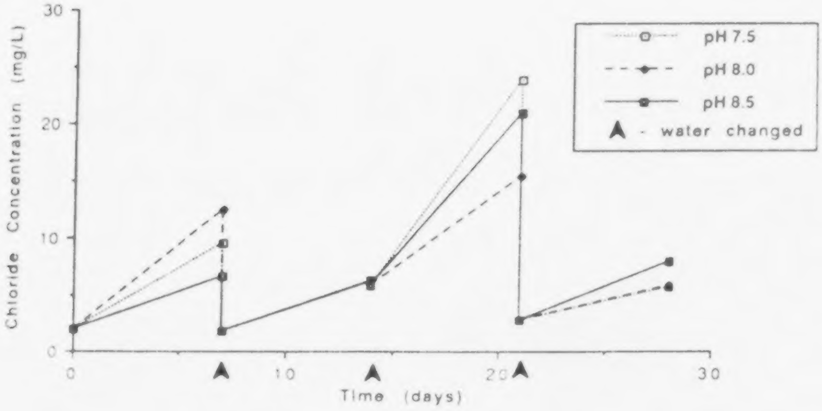


Figure B.2.3.2.1
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



a. pH 7.5: the average increase was 8.31 mg/L with a range of 2.93 to 17.94 mg/L as Cl^-;

b. pH 8.0: the average increase was 6.91 mg/L with a range of 3.10 to 10.52 mg/L as Cl^-; and

c. pH 8.5: the average increase was 7.30 mg/L with a range of 4.37 to 15.01 mg/L as Cl^-.

Not known, however, is what the chloride concentration was, immediately after chlorinating the water.

B.2.4 Copper Concentration

B.2.4.1 Copper Experiments

Figure B.2.4.1.1 shows the weekly changes in copper concentration of the experimental waters, for the immersion of copper at different pH settings. The average increase and range by which the copper concentration changed for each pH setting for a weekly liquid retention time was:

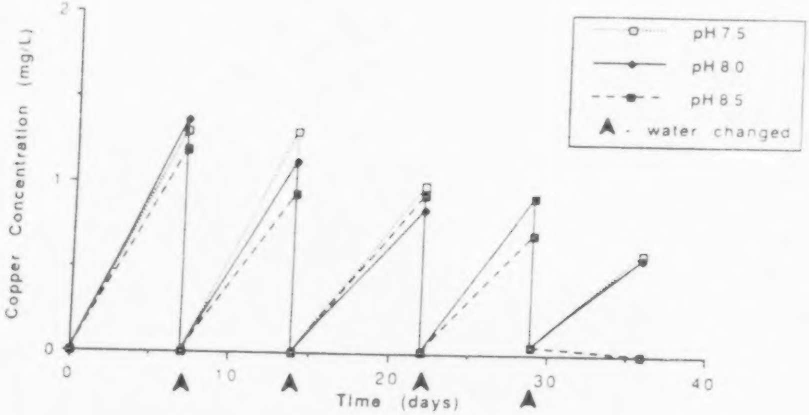
a. pH 7.5: the average increase was 1.00 mg/L with a range of 0.55 to 1.29 mg/L as Cu^{2+};

b. pH 8.0: the average increase was 0.95 mg/L with a range of 0.51 to 1.36 mg/L as Cu^{2+}; and

c. pH 8.5: the average increase was 0.74 mg/L with a range of -0.05 to 1.19 mg/L as Cu^{2+}.

The copper concentrations increased from copper corrosion. Also, the increases are shown decreasing with increasing pH.

Figure B.2.4.1.1
Weekly Changes in Copper Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings



B.2.5 Dissolved Oxygen Concentration

B.2.5.1 Copper Experiments

Figure B.2.5.1.1 shows the dissolved oxygen concentrations, as measured when changing the experimental waters on a weekly basis, for the immersion of copper at different pH settings. The dissolved oxygen concentrations of the experimental waters were kept relatively constant by continual aeration of the waters. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. pH 7.5: the average was 11.59 mg/L with a range of
11.54 to 11.64 mg/L as O_2;
b. pH 8.0: the average was 11.62 mg/L with a range of
11.58 to 11.66 mg/L as O_2; and
c. pH 8.5: the average was 11.61 mg/L with a range of
11.59 to 11.63 mg/L as O_2.

B.2.5.2 Ductile Iron Experiments

Figure B.2.5.2.1 shows the dissolved oxygen concentrations, as measured when changing the experimental waters on a weekly basis, for the immersion of ductile iron at different pH settings. The dissolved oxygen concentrations of the experimental waters were kept relatively constant by continual aeration of the waters. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. pH 7.5: the average was 11.31 mg/L with a range of
11.28 to 11.34 mg/L as O_2;

Figure B.2.5.1.1
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

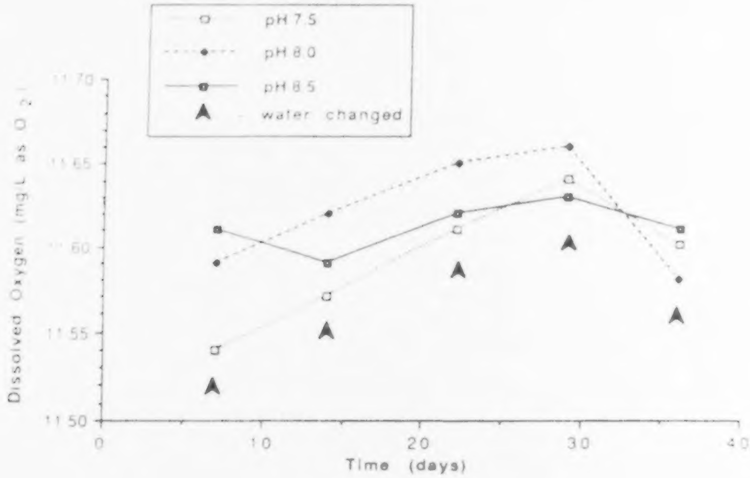
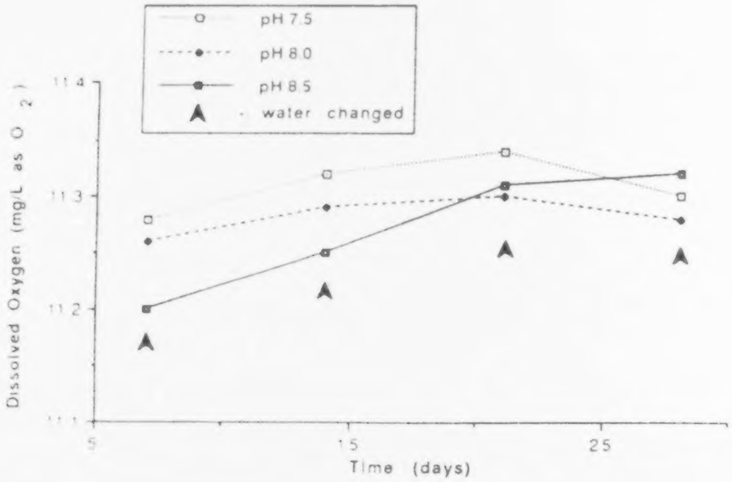


Figure B.2.5.2.1
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



b. pH 8.0: the average was 11.28 mg/L with a range of 11.26 to 11.30 mg/L as O_2; and

c. pH 8.5: the average was 11.27 mg/L with a range of 11.20 to 11.32 mg/L as O_2.

B.2.6 Electrical Conductivity

B.2.6.1 Copper Experiments

Figure B.2.6.1.1 shows the weekly changes in electrical conductivity of the experimental waters, for the immersion of copper at different pH settings. The increases in electrical conductivity of each setting were primarily from the continual addition of sodium carbonate to maintain the desired pH settings. The average increase and range by which the electrical conductivity changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 29.0 with a range of 16.0 to .53.0 umhos/cm;

b. pH 8.0: average increase was 70.0 with a range of 47.0 to 120.0 umhos/cm; and

c. pH 8.5: average increase was 158.2 with a range of 93.0 to 204.0 umhos/cm.

Previously stated, is that increasing the pH, alkalinity and electrical conductivity of the waters enhanced the conditions needed for developing a protective coating on the surfaces of copper to reduce corrosion.

B.2.6.2 Ductile Iron Experiments

Figure B.2.6.2.1 shows the weekly changes in electrical conductivity, for the immersion of ductile iron at the different pH settings. The average increase and range by which the electrical conductivity changed for each pH setting for a weekly retention time was:

a. pH 7.5: the average increase was 151.0 with a range of 120.0 to 176.0 umhos/cm;

b. pH 8.0: the average increase was 333.0 with a range of 262.0 to 363.0 umhos/cm;. and

c. pH 8.5: the average increase was 747.0 with a range of 610.0 to 842.0 umhos/cm.

The increases were much greater than for the copper results. This is attributed to more sodium carbonate needed on a periodic basis to maintain the desired pH settings. The magnitude of the increases are shown increasing with increasing pH.

B.2.7 Magnesium Concentration

B.2.7.1 Copper Experiments

Figure B.2.7.1.1 shows the weekly changes in magnesium concentration of the experimental waters, for the immersion of copper at different pH settings. The average increase and range by which the magnesium concentration changed for each pH setting for a weekly liquid retention time was:

Figure B.2.6.1.1
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Copper At Different pH Settings

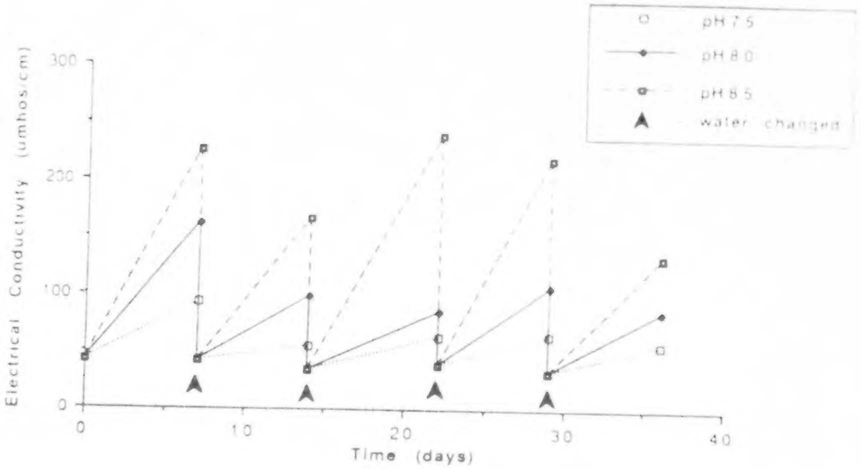
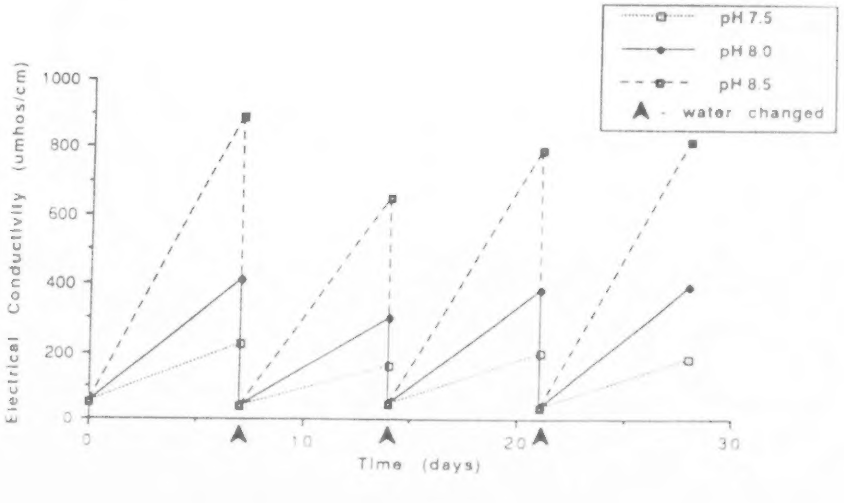


Figure B.2.6.2.1
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



a. pH 7.5: average increase was 0.14 mg/L with a range of
-0.08 to 0.36 mg/L as Mg^{2+};
b. pH 8.0: average increase was 0.12 mg/L with a range of
-0.18 to 0.33 mg/L as Mg^{2+}; and
c. pH 8.5: average increase was 0.05 mg/L with a range of
-0.21 to 0.29 mg/L as Mg^{2+}.

B.2.7.2 Ductile Iron Experiments

Figure B.2.7.2.1 shows the weekly changes in magnesium concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The magnesium concentration for the pH setting 7.5 increased slightly for the liquid's weekly retention time. Where as, for the pH settings 8.0 and 8.5 the magnesium concentrations decreased. The average change and range by which the magnesium concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 0.09 mg/L with a range of
...0.05 to 0.12 mg/L as Mg^{2+};
b. pH 8.0: average change was -0.02 mg/L with a range of
...-0.07 to 0.06 mg/L as Mg^{2+}; and
c. pH 8.5: average change was -0.07 mg/L with a range of
...-0.027 to 0.01 mg/L as Mg^{2+}.

The decreases in magnesium concentration are shown increasing with increasing pH.

Figure B.2.7.1.1
Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

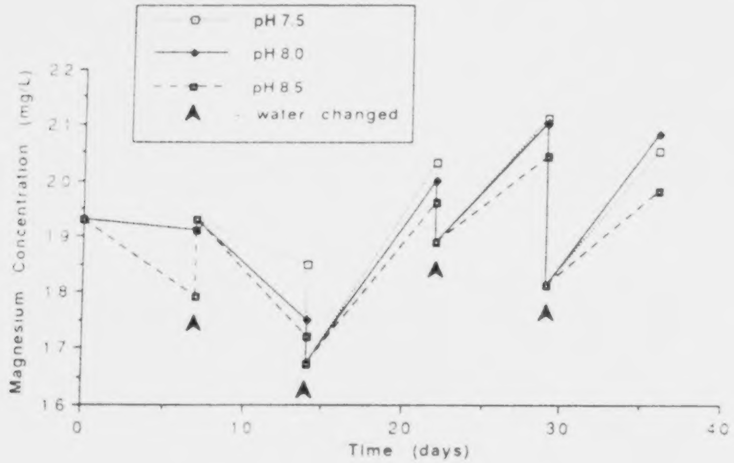
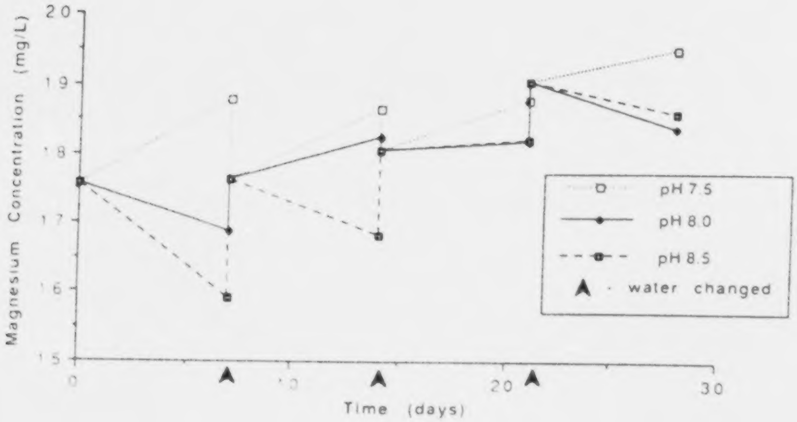


Figure B.2.7.2.1
Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



B.2.8 pH

B.2.8.1 Copper Experiments

Figures B.2.8.1.1, B.2.8.1.2 and B.2.8.1.3 show the changes in pH with time, for the immersion of copper at the pH settings 7.5, 8.0, and 8.5, using sodium carbonate.

B.2.8.2 Ductile Iron Experiments

Figures B.2.8.2.1, B.2.8.2.2 and B.2.8.2.3 show the changes in pH with time, for the immersion of ductile iron at the pH settings 7.5, 8.0, and 8.5, using sodium carbonate. The pH fluctuations were greatest for each setting, immediately after changing the experimental water with the maximum decrease limited to the first two days. The Yellowknife River water, used as the experimental water, is poorly buffered. The decreases in pH are from the consumption of alkalinity used for scale formation as well as from the addition of carbon dioxide in aeration of the experimental waters. Initially, the experimental water was poorly buffered. So high corrosion, together with the addition of carbon dioxide, during aeration, resulted in the greatest pH decreases. However, the periodic addition of sodium carbonate increased the water's buffer capacity, making it more resistant to pH changes with time. Also, the higher the pH setting, initially the greater the pH decrease for immediately after changing the water. For pH setting 8.5 the pH varied from 8.65 to 7.80 with the average being 8.50. For pH setting 8.0 the pH varied from 8.15 to 7.30 with the average being 8.00. For pH setting 7.5, the pH varied from 7.65 to 7.25 with the average being 7.45.

Figure B.2.8.1.1
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH Setting 8.5 Using Sodium Carbonate

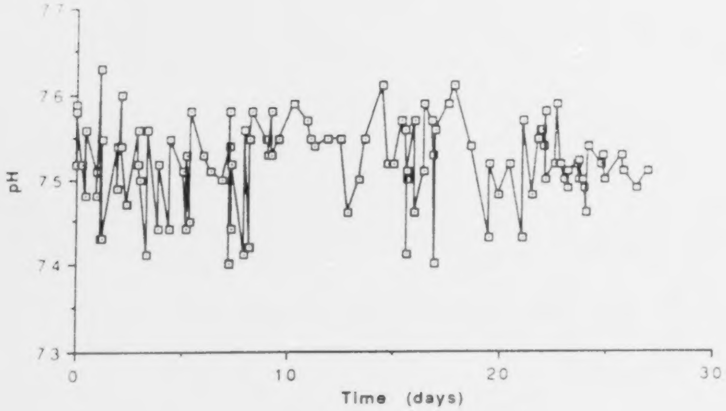


Figure B.2.8.1.2
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH Setting 8.0 Using Sodium Carbonate

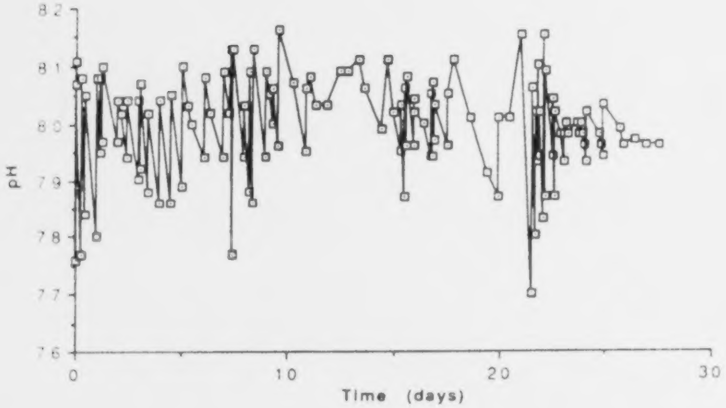


Figure B.2.8.1.3
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH Setting 7.5 Using Sodium Carbonate

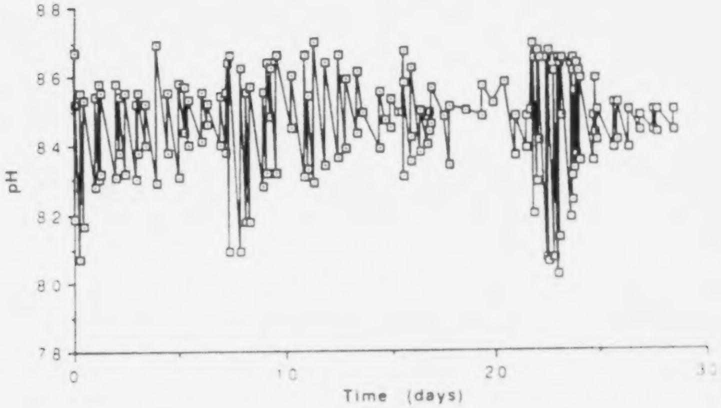


Figure B.2.8.2.1
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH Setting 8.5 Using Sodium Carbonate

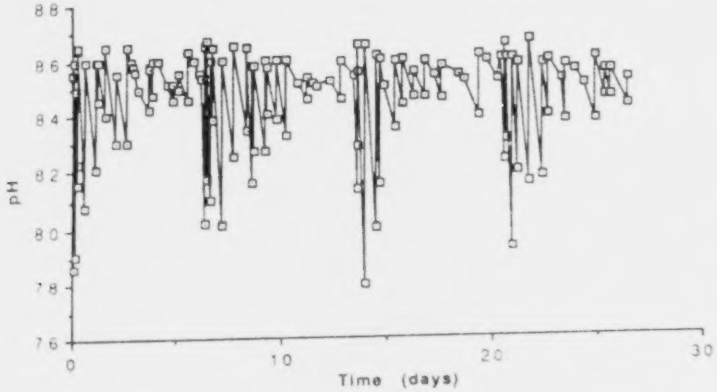


Figure B.2.8.2.2
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH Setting 8.0 Using Sodium Carbonate

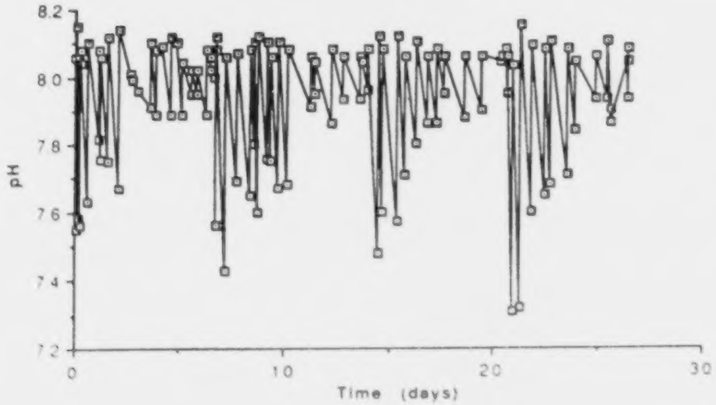
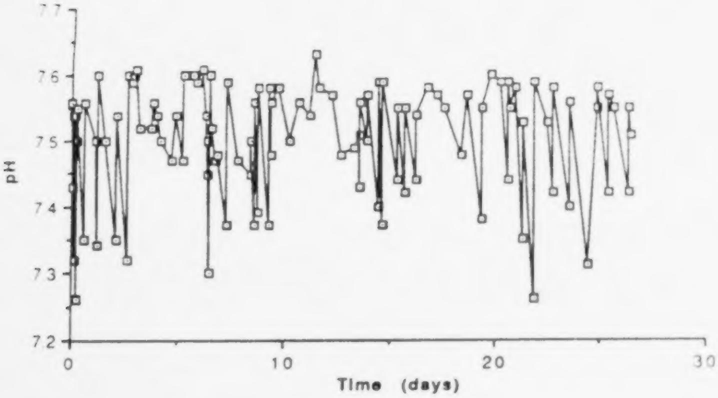


Figure B.2.8.2.3
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH Setting 7.5 Using Sodium Carbonate



B.2.9 Silicate Concentration

B.2.9.1 Copper Experiments

Figure B.2.9.1.1 shows the weekly changes in silicate concentration of the experimental waters for the immersion of copper at different pH settings. The average increase and range by which the silicate concentration changed for each pH setting for a liquid retention time was:

a. pH 7.5: average increase was 0.07 mg/L with a range of -0.02 to 0.20 mg/L as Si;

b. pH 8.0: average increase was 0.06 mg/L with a range of -0.01 to 0.11 mg/L as Si; and

c. pH 8.5: average increase was 0.08 mg/L with a range of 0.02 to 0.20 mg/L as Si.

The silicate concentrations increased slightly for the weekly liquid retention times from liquid losses due to evaporation.

B.2.9.2 Ductile Iron Experiments

Figure B.2.9.2.1 shows the weekly changes in silicate concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The average increase and range by the silicate concentration for each pH setting for a weekly retention time was;

a. pH 7.5: average increase was 1.40 with range of 1.03 to 1.56 mg/L as Si;

b. pH 8.0: average increase was 1.49 with range of 0.79 to 2.20 mg/L as Si; and

Figure B.2.9.1.1
Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

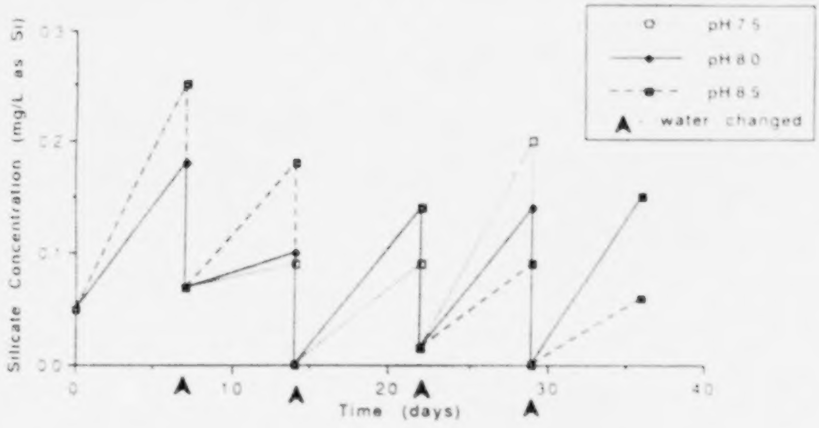
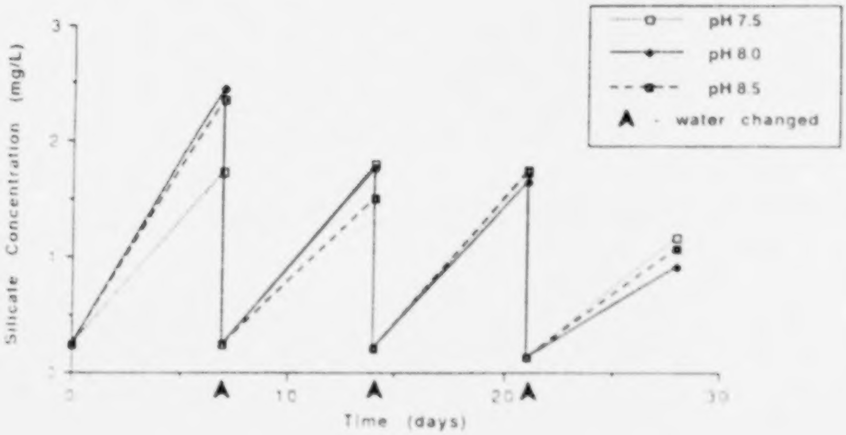


Figure B.2.9.2.1
Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



c. pH 8.5: average increase was 1.46 with range of 0.94 to
2.11 mg/L as Si.

The increases in silicate concentration were much higher than the copper results. This is attributed to silicate being an ingredient of ductile iron which, from corrosion was released.

B.2.10 Sodium Concentration

B.2.10.1 Copper Experiments

Figure B.2.10.1.1 shows the weekly increases in sodium concentration of the experimental waters primarily from sodium carbonate addition to maintain the desired pH settings. The average increase and range by which the sodium concentration changed for each pH setting for a weekly retention time was:

a. pH 7.5, average increase was 7.25 mg/L with a range of .5.00 to 11.25 mg/L as Na^+;
b. pH 8.0, average increase was 24.54 mg/L with a range of 17.50 to 36.30 mg/L as Na^+; and
c. pH 8.5, average increase was 57.14 mg/L with a range of 51.30 to 65.00 mg/L as Na^+.

Lines are not drawn connecting the data points for each setting as unknown was rate by which the sodium concentration changed for the liquid's retention time.

B.2.10.2 Ductile Iron Experiments

Figure B.2.10.2.1 shows the weekly changes in sodium concentration of the experimental waters, for the immersion of ductile iron, primarily from sodium carbonate addition to maintain the desired pH settings. The average increase and range by which the sodium concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 56.99 mg/L with a range of 52.25 to 60.20 mg/L as Na^+;

b. pH 8.0: average increase was 119.46 mg/L with a range of 111.39 to126.98 mg/L as Na^+; and

c. pH 8.5: average increase was 262.45 mg/L with a range of 237.99 to 274.98 mg/L as Na^+.

Lines are not drawn connecting the data points for each setting as unknown was rate by which the sodium concentration changed for the liquid's retention time.

B.2.11 Sulfate Concentration

B.2.11.1 Copper Experiments

Figure B.2.11.1 shows the weekly changes in sulfate concentration of the experimental waters, for the immersion of copper at different pH settings. The average increase and range by which the sulfate concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 0.32 mg/L with a range of 0.00 to 0.71 mg/L as SO_4^{2-};

Figure B.2.10.1.1
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

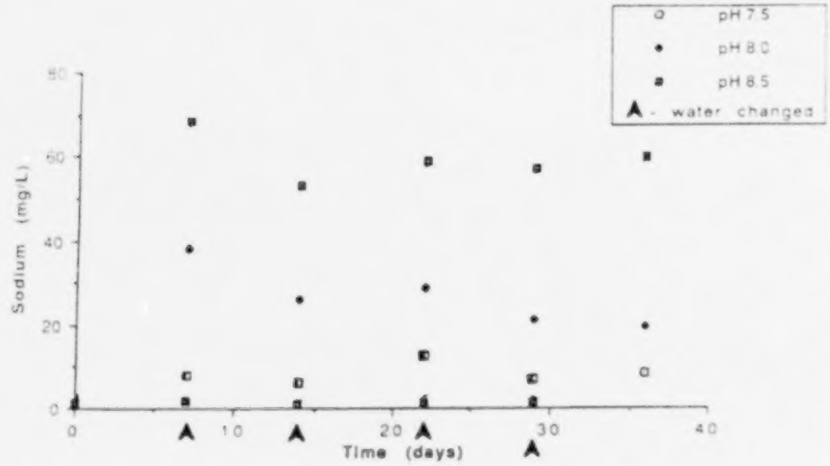
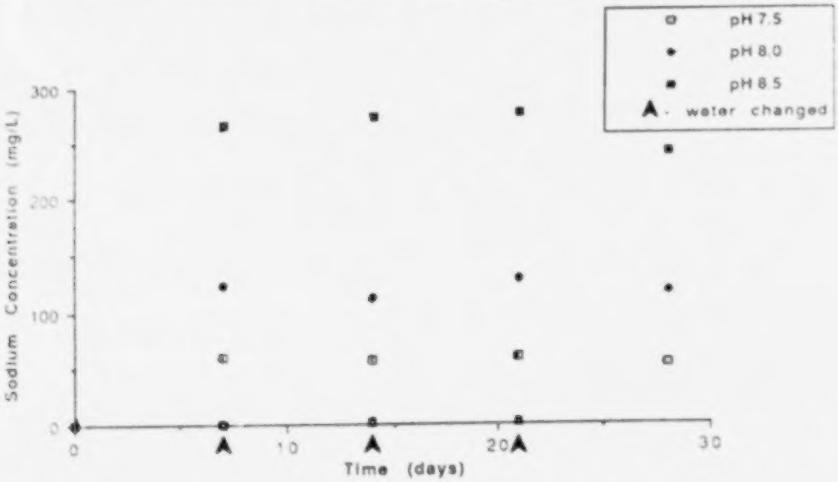


Figure B.2.10.2.1
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



b. pH 8.0: average increase was 0.31 mg/L with a range of -0.10 to 0.49 mg/L as SO_4^{2-}; and

c. pH 8.5: average increase was 0.19 mg/L with a range of 0.11 to 0.62 mg/L as SO_4^{2-}.

B.2.11.2 Ductile Iron experiments

Figure B.2.11.2.1 shows the weekly changes in sulfate concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The average decrease and range by which the sulfate concentration changed for each pH setting for a weekly retention time was:

a. pH 7.5: average change was -0.61 mg/L with a range of -1.60 to -0.13 mg/L as SO_4^{2-};

b. pH 8.0: average change was -0.62 mg/L with a range of -0.93 to -0.43 mg/L as SO_4^{2-}; and

c. pH 8.5: average change was -0.82 mg/L with a range of -1.22 to -0.41 mg/L as SO_4^{2-}.

Microbial activity within the corrosion scale formed on the surfaces of ductile iron coupons may have contributed to the decreases in sulfate concentration.

B.2.12 Temperature

The temperature at which the experiments were preformed, ranged from 5 to 7 °C.

Figure B.2.11.1.1
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

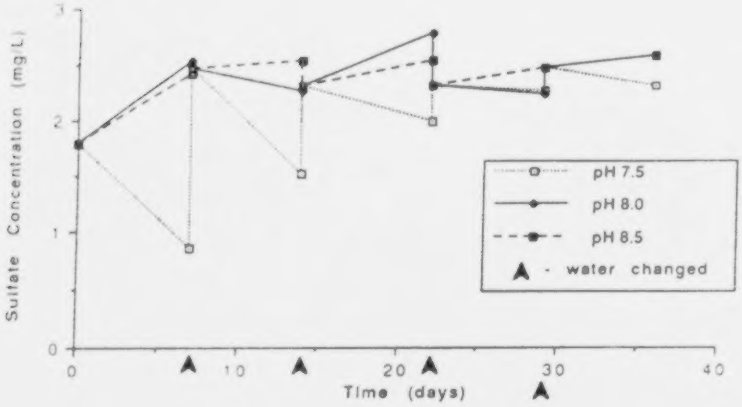
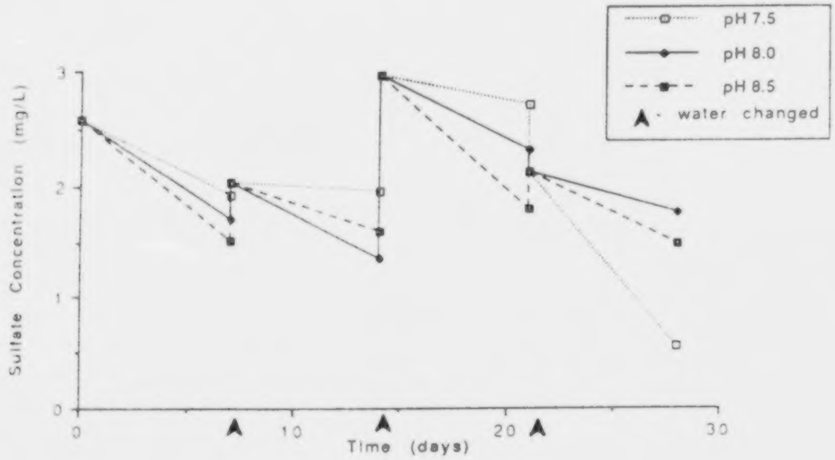


Figure B.2.11.2.1
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



B.2.13 Total Hardness Concentration

B.2.13.1 Copper Experiments

Figure B.2.13.1.1 shows the weekly changes in total hardness concentration of the experimental waters at the different pH settings. The average increase and range by which the total hardness concentration changed for each pH setting for a weekly retention time was:

a. pH 7.5: the average increase was 1.5 mg/L with a range of 0.1 to 2.4 mg/L as $CaCO_3$;

b. pH 8.0: the average change was -1.4 mg/L with a range of -2.2 to -0.2 mg/L as $CaCO_3$; and

c. pH 8.5: the average change was -1.5 mg/L with a range of -2.0 to -1.2 mg/L as $CaCO_3$.

The total hardness concentrations increased slightly from liquid losses due to evaporation. Copper when exposed alone, does not generate sufficient cell activity to cause $CaCO_3$ to deposit on its surface.

B.2.13.2 Ductile Iron Experiments

Figure B.2.13.2.1 shows the weekly changes in total hardness concentration of the experimental waters for the immersion of ductile iron at different pH settings. The average decrease and range by which the total hardness concentration changed for each pH setting for a weekly retention time was:

a. pH 7.5: the average change was -1.0 mg/L with a range of -1.7 to -1.0 mg/L as $CaCO_3$;

Figure B.2.13.1.1
Weekly Changes in Total Hardness Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

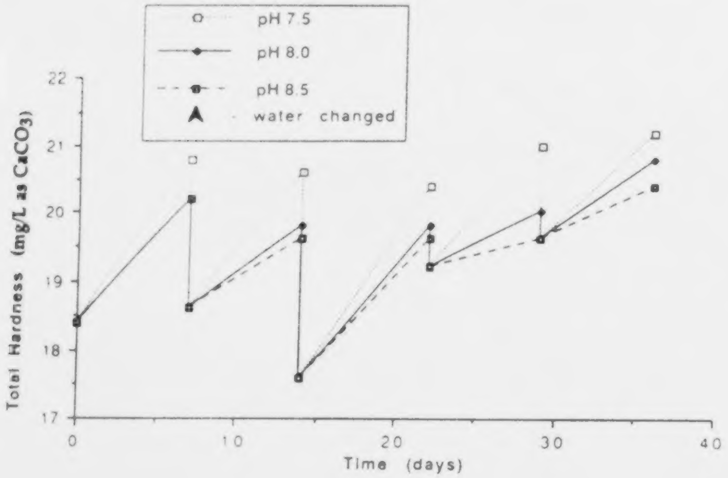
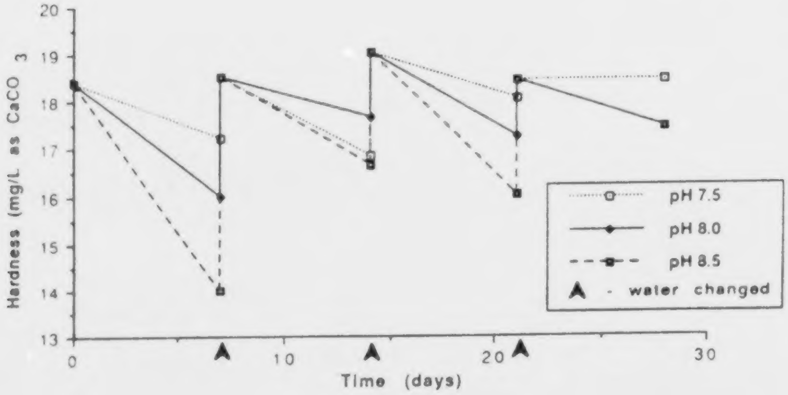


Figure B.2.13.2.1
Weekly Changes in Total Hardness Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



b. pH 8.0: the average change was -1.5 mg/L with a range of -2.4 to -0.9 mg/L as $CaCO_3$; and

c. pH 8.5: the average change was -2.6 mg/L with a range of -4.4 to -1.0 mg/L as $CaCO_3$.

Stated previously, is that $CaCO_3$ can be precipitated for waters slightly undersaturated with respect to $CaCO_3$ from local pH increases at the metal's surface caused by corrosion. The tendency of the data, shows the amount of reduction in the hardness concentration decreases with increasing pH.

B.2.14 Turbidity

B.2.14.1 Copper Experiments

Figure B.2.14.1.1 shows the weekly changes in turbidity of the experimental waters, for the immersion of copper at different pH settings. The average increase and range by which the turbidity changed for each pH setting was:

a. pH 7.5: average increase was 1.3 with a range of -0.1 to 3.1 NTU;

b. pH 8.0: average increase was 0.6 with a range of 0.0 to 0.9 NTU; and

c. pH 8.5: average increase was 0.9 with a range of 0.8 to 1.3 NTU.

Regardless of pH setting, the turbidity increased slightly for the weekly liquid retention time. This is attributed to copper corrosion and, to a lesser extent, from liquid losses due to evaporation.

B.2.14.2 Ductile Iron Experiments

Figure B.2.14.2.1 shows the weekly changes in turbidity of the experimental waters, for the immersion of ductile iron at different pH settings. The increases in turbidity of each setting are attributed primarily to ductile iron corrosion. As well, the turbidity increases are shown decreasing with time. This is from the removal of coupons and a reduction in corrosion rate with time. The average increase and range by which the turbidity changed for each pH setting for a weekly retention time was:

a. pH 7.5: the average increase was 9.6 with a range of 3.8 to 11.6 NTU;

b. pH 8.0: the average increase was 4.7 with a range of 2.1 to 8.5 NTU; and

c. pH 8.5: the average increase was 8.0 with a range of 1.8 to 9.5 NTU.

Figure B.2.14.1.1
Weekly Changes in Turbidity of the Experimental Waters for the Immersion of Copper At Different pH Settings

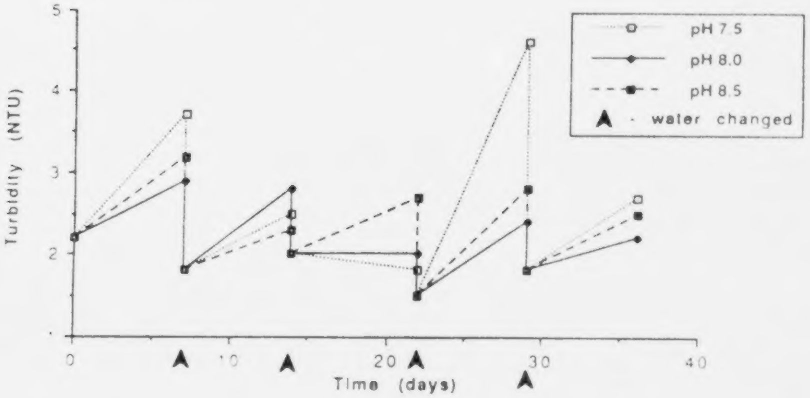
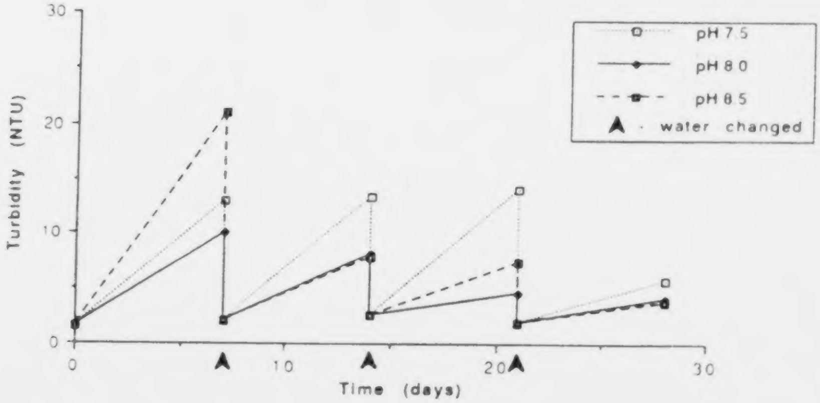


Figure B.2.14.2.1
Weekly Changes in Turbidity of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



Appendix C

Detailed Summary of the Water Quality Changes for the Sodium Hydroxide Tests.

The following is a detailed summary of the water quality changes for each setting of the sodium hydroxide experiments. Detailed are the weakly changes in water quality throughout the duration of each corrosion test conducted using the inhibitor, sodium hydroxide.

C.1 Experimental Schedule

C.1.1 Copper Experiments

Figures C.1.1.1, C.1.1.2 and C.1.1.3 are the experimental schedules for the removal of copper coupons exposed to different pH settings. Sample sets consisted of two to four coupons and sets were removed weekly. The duration of the experiments was approximately 30 days.

C.1.2 Ductile Iron Experiments

Figures C.1.2.1, C.1.2.2 and C.1.2.3 are the experimental schedules for the removal of ductile iron coupons exposed to different pH settings. Sample sets consisted of 2 to 3 coupons and sets were removed weekly. The duration of experiments varied from 23 to 44 days.

C.2 Laboratory Water Characteristics

Throughout the experiments, several water quality parameters were monitored on a weekly basis. These parameters were measured prior to the immersion of coupons, and again when changing the water on a weekly basis. Presented, are the weekly variations in water quality for the immersion of both ductile iron and copper coupons at different pH settings.

Figure C.1.1.1
Experimental Schedule: pH 7.5, NaOH

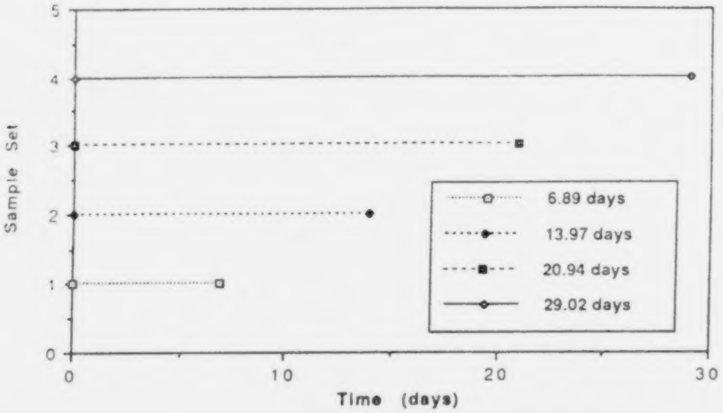


Figure C.1.1.2
Experimental Schedule: pH 8.0, NaOH

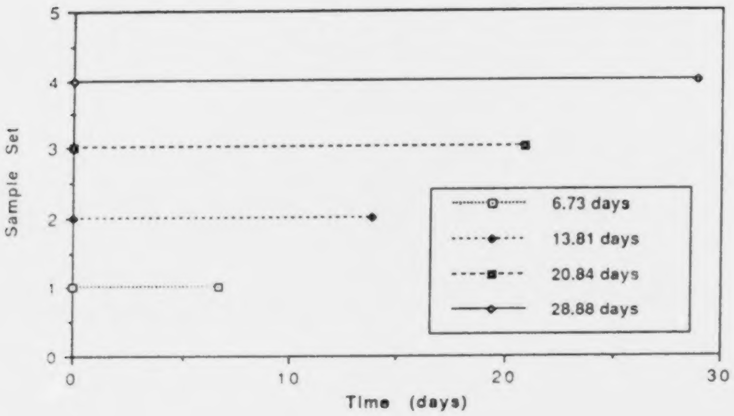


Figure C.1.1.3
Experimental Schedule: pH 8.5, NaOH

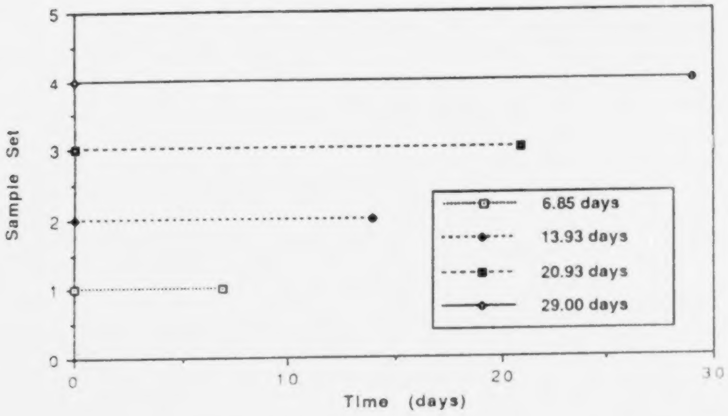


Figure C.1.2.1
Experimental Schedule: pH 7.5, NaOH

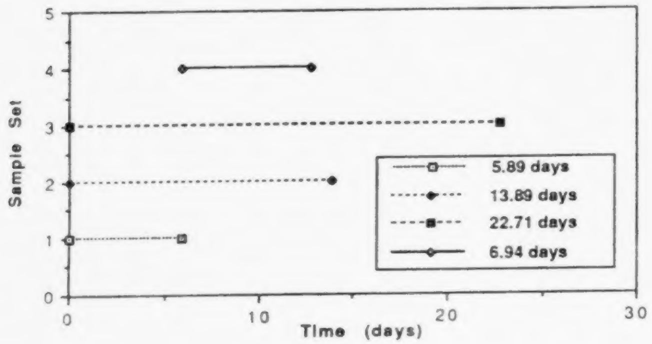


Figure C.1.2.2
Experimental Schedule: pH 8.0, NaOH

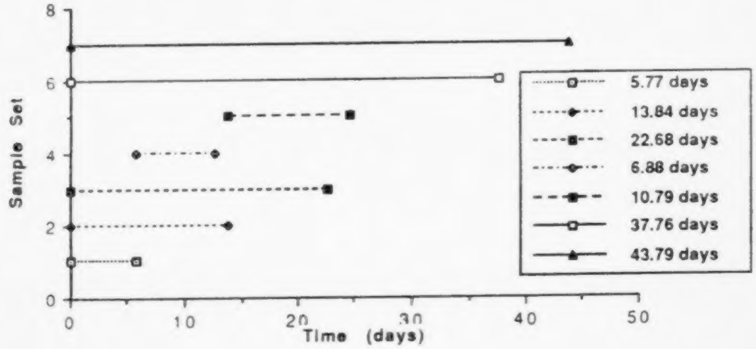
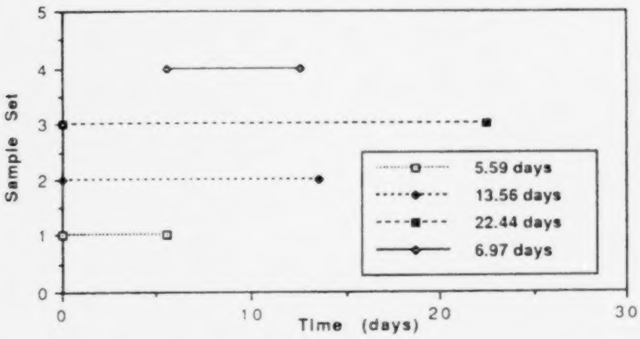


Figure C.1.2.3
Experimental Schedule: pH 8.5, NaOH



C.2.1 Alkalinity

C.2.1.1 Copper Experiments

Figure C.2.1.1.1 shows the weekly changes in alkalinity of the experimental waters, for the immersion of copper at different pH settings. The alkalinity of each of setting increased from the continual addition of sodium hydroxide, required to maintain the desired pH settings. The degree of change in alkalinity was dependent on the desired pH setting. For example, maintaining the higher pH setting caused greater changes in the water's alkalinity concentration. The average increase and range by which the alkalinity for each setting changed for a weekly liquid retention time was:

a. pH 7.5: the average increase was 5.5 mg/L with a range of 5.1 to 5.7 mg/L as $CaCO_3$;

b. pH 8.0: the average increase was 32.5 mg/L with a range of 29.1 to 37.1 mg/L as $CaCO_3$; and

c. pH 8.5: the average increase was 108.0 mg/L with a range of 99.7 to 121.5 mg/L as $CaCO_3$.

C.2.1.2 Ductile Iron Experiments

Figure C.2.1.2.1 shows the weekly changes in alkalinity of the experimental waters, for the immersion of ductile iron at different pH settings using sodium hydroxide. Similar to the copper results, is the alkalinity of each setting increased from sodium hydroxide addition and the increases were much higher. The average increase and range by which the alkalinity changed for each setting for a weekly liquid retention time was:

a. pH 7.5: the average increase was 145.4 mg/L with a range of 125.4 to 177.2 mg/L as $CaCO_3$;

b. pH 8.0: the average increase was 238.5 mg/L with a range of 218.4 to 266.4 mg/L as $CaCO_3$; and

c. pH 8.5: the average increase was 476.2 mg/L with a range of 455.4 to 487.2 mg/L as $CaCO_3$.

The large differences between the increases in alkalinities between each experiment, is a function on the metal type. Ductile iron, as it corrodes, is passivated with corrosion products. These corrosion products are the result of metal hydroxides being deposited on the surface of the metal. The rate of formation of these metal hydroxides, consumes more alkalinity than the products slowly produced from copper corrosion. Ductile iron corrodes much more rapidly than copper, and consequently consumes more alkalinity, causing the pH to change more frequently. Thus, necessitating the addition of sodium hydroxide more frequently to maintain the desired pH setting. Consequently, larger additions of sodium hydroxide were required for the ductile iron experiments, than for the copper experiments.

Figure C.2.1.2.1
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings

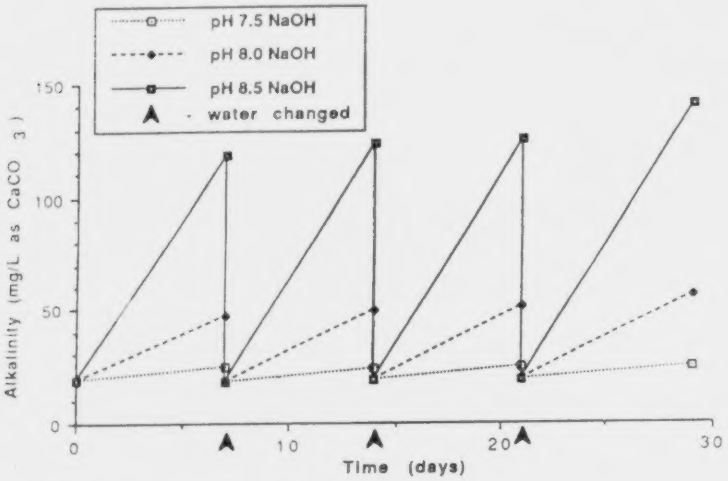
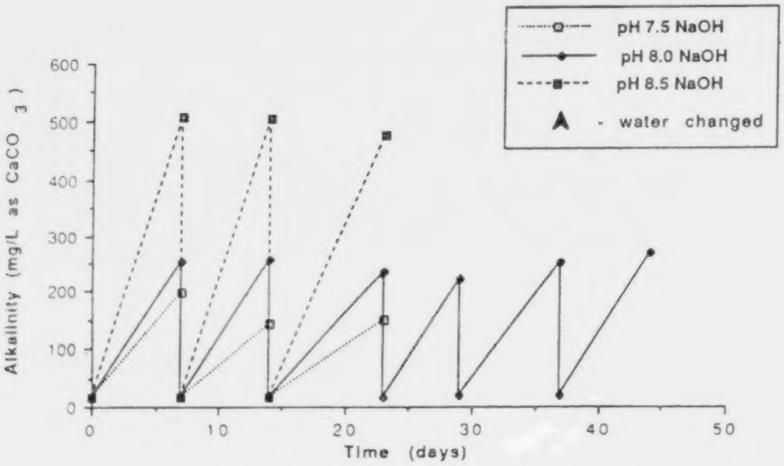


Figure C.2.1.1.1
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Copper At Different pH Settings



C.2.2 Calcium Concentration

C.2.2.1 Copper Experiments

Figure C.2.2.1.1 shows the weekly changes in calcium concentration of the experimental waters, for the immersion of copper at different pH settings. The calcium concentration of each setting increased slightly from liquid losses due to evaporation for a weekly liquid retention time. The average increase and range by which the calcium concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 0.6 mg/L with a range of
0.5 to 0.8 mg/l as Ca^{2+};
b. pH 8.0: average increase was 0.7 mg/L with a range of
0.3 to 1.4 mg/L as Ca^{2+}; and
c. pH 8.5: average increase was 0.5 mg/L with a range of
0.3 to 0.6 mg/L as Ca^{2+}.

The increase in calcium concentrations suggests, that calcium had not precipitated as $CaCO_3$ on the surfaces of copper coupons. This, however, was not unexpected, since copper exposed alone is not coated with $CaCO_3$.

C.2.2.2 Ductile Iron Experiments

Figure C.2.2.2.1 shows the weekly changes in calcium concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The average change and range by which the calcium concentration changed for each pH setting for a weekly liquid retention time was;

a. pH 7.5: average increase was 0.6 mg/L with a range of

Figure C.2.2.1.1
Weekly Changes in Calcium Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

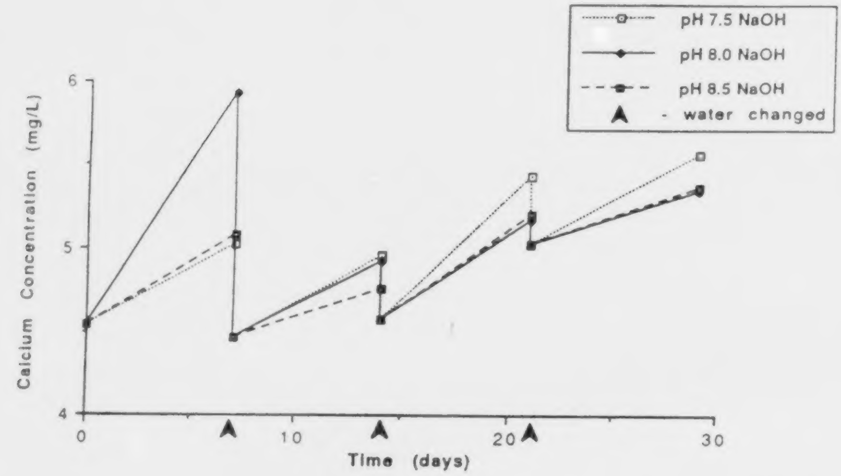
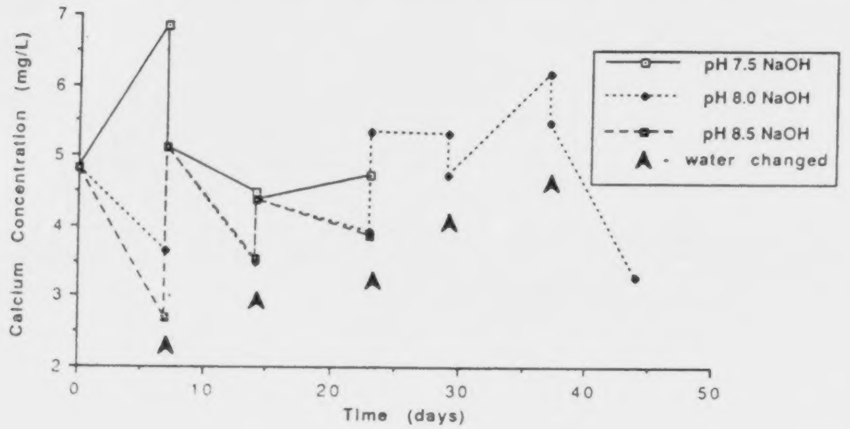


Figure C.2.2.2.1
Weekly Changes in Calcium Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



-0.6 to 2.0 mg/l as Ca^{2+};

b. pH 8.0: average change was -0.7 mg/L with a range of
-2.2 to 1.5 mg/L as Ca^{2+}; and

c. pH 8.5: average change was -1.4 mg/l with a range of
-2.1 to -0.5 mg/L as Ca^{2+}.

With the exception of pH setting 7.5, the calcium concentration decreased for a weekly liquid retention time. Shown, as well, is the magnitude by which the calcium concentration decreased increased with increasing pH.

C.2.3 Chloride Concentration

C.2.3.1 Copper Experiments

Figure C.2.3.1.1 shows the weekly changes in chloride concentration of the experimental waters, for the immersion of copper at different pH settings. The average increase and range by which the chloride concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 5.19 mg/L with a range of
3.12 to 10.26 mg/L as Cl^-;

b. pH 8.0: average increase was 5.26 mg/l with a range of
2.16 to 10.06 mg/L as Cl^-; and

c. pH 8.5: average increase was 5.78 mg/L with a range of
3.00 to 12.66 mg/l as Cl^-.

The chloride concentration of each setting increased from chlorination. In addition to the increase in chloride concentration of each setting, there was a increase in alkalinity which would have reduced chloride's influence on corrosion. As well, shown, are the increases generally the same for each setting.

C.2.3.2 Ductile Iron Experiments

Figure C.2.3.2.1 shows the weekly changes in chloride concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The average increase and range by which the chloride concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 9.11 mg/L with a range of 2.15 to 15.62 mg/L as Cl^-;

b. pH 8.0: average increase was 3.81 mg/l with a range of 1.93 to 11.68 mg/L as Cl^-; and

c. pH 8.5: average increase was 6.33 mg/L with a range of 1.05 to 10.28 mg/l as Cl^-.

The chloride concentration of each setting increased from chlorination. Similar to the copper results, is that for each setting, the alkalinity increased along with the chloride concentration which will have greatly reduce chloride's influence on corrosion. Not known, however, is what the chloride concentration was, immediately after chlorinating the water.

C.2.4 Copper Concentration

C.2.4.1 Copper Experiments

Figure C.2.4.1.1 shows the weekly changes in copper concentration of the experimental waters, for the immersion of copper at different pH settings. The copper concentration of each setting increased from corrosion. The

Figure C.2.3.1.1
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

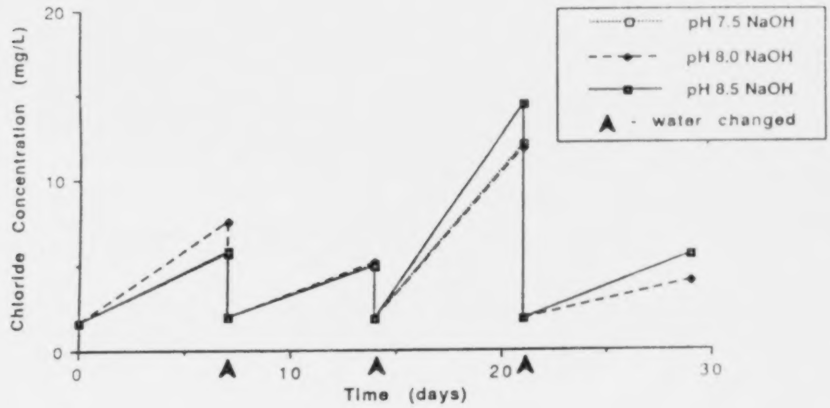
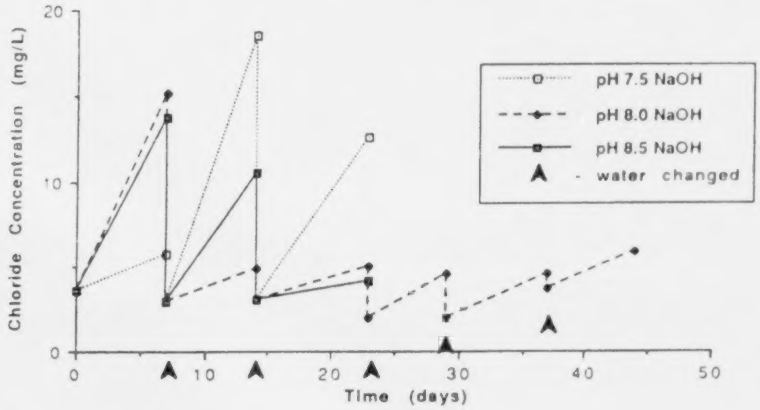


Figure C.2.3.2.1
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



average increase and range by which the copper concentration changed for each pH setting for a weekly retention time was:

a. pH 7.5: average increase was 1.17 mg/L with a range of 0.77 to 1.43 mg/L as Cu^{2+};

b. pH 8.0: average increase was 0.98 mg/l with a range of 0.71 to 1.16 mg/L as Cu^{2+}; and

c. pH 8.5: average increase was 0.74 mg/L with a range of 0.53 to 0.85 mg/L as Cu^{2+}.

Copper corrosion is pH dependent and this reflected in Figure 2.4.1.1. Shown, are the increases in copper concentration decreasing with increasing pH.

C.2.5 Dissolved Oxygen Concentration

C.2.5.1 Copper Experiments

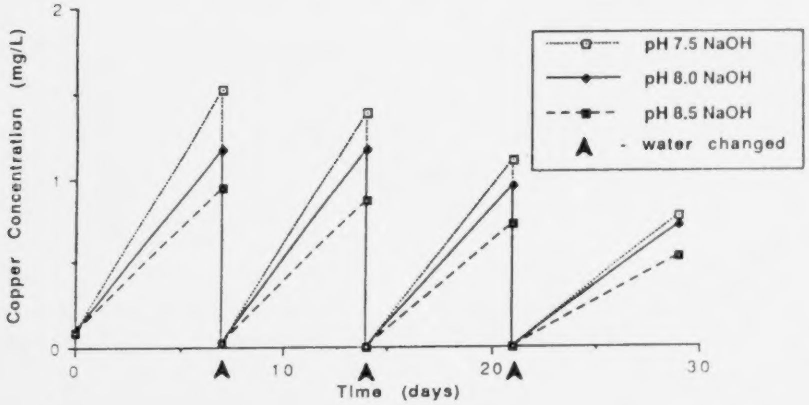
Figure C.2.5.1.1 shows the dissolved oxygen concentrations as measured when changing the experimental waters on a weekly basis, for the immersion of copper at different pH settings. The dissolved oxygen concentrations of the experimental waters were kept relatively constant by continual aeration of the waters. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. pH 7.5: the average was 11.61 mg/L with a range of 11.58 to 11.64 mg/L as O_2;

b. pH 8.0: the average was 11.65 mg/L with a range of 11.63 to 11.68 mg/L as O_2; and

c. pH 8.5: the average was 11.64 mg/L with a range of 11.60 to 11.66 mg/L as O_2.

Figure C.2.4.1.1
Weekly Changes in Copper Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings



C.2.5.2 Ductile Iron Experiments

Figure C.2.5.2.1 shows the dissolved oxygen concentrations as measured when changing the experimental waters on a weekly basis, for the immersion of ductile iron at different pH settings. The dissolved oxygen concentrations of the experimental waters were kept relatively constant by continual aeration of the waters. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. pH 7.5: the average was 11.26 mg/L with a range of 11.23 to 11.29 mg/L as O_2;

b. pH 8.0: the average was 11.24 mg/L with a range of 11.18 to 11.28 mg/L as O_2; and

c. pH 8.5: the average was 11.24 mg/L with a range of 11.18 to 11.28 mg/L as O_2.

C.2.6 Electrical Conductivity

C.2.6.1 Copper Experiments

Figure C.2.6.1.1 shows the weekly changes in electrical conductivity of the experimental waters, for the immersion of copper at different pH settings. The electrical conductivity of each setting increased mainly from sodium hydroxide addition required to maintain the desired pH settings. The average increase and range by which electrical conductivity changed for each pH setting for a weekly retention time was:

a. pH 7.5: average increase was 16.5 with a range of 15.0 to 18.0 umhos/cm;

Figure C.2.5.1.1
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

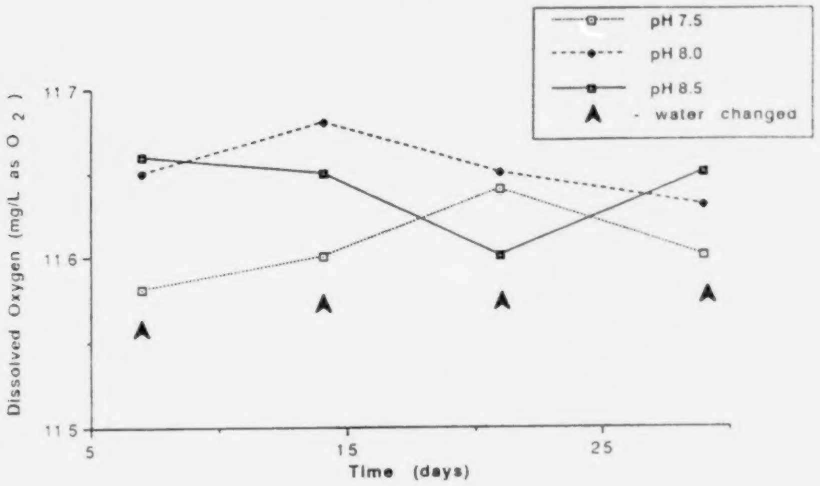
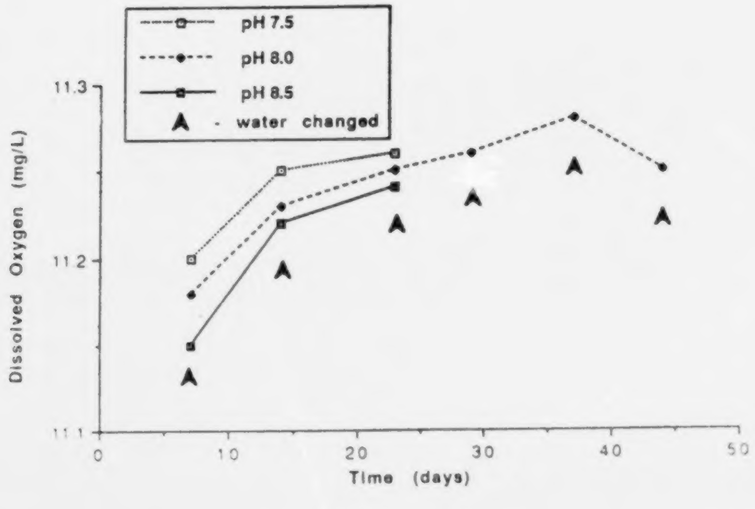


Figure C.2.5.2.1
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



b. pH 8.0: average increase was 52.3 with a range of 46.0 to 59.0 umhos/cm; and

c. pH 8.5: average increase was 149.0 with a range of 125.0 to 169.0 umhos/cm.

Increasing the electrical conductivity, can intensify electronic and ionic conduction required for the formation of a good protective cuprous oxide film to reduce copper corrosion (AWWA, 1985).

C.2.6.2 Ductile Iron Experiments

Figure C.2.6.2.1 shows the weekly changes in electrical conductivity of experimental waters, for the immersion of ductile iron at different pH settings. Similar to the copper results, was that the electrical conductivity of each setting increased from mainly sodium hydroxide addition. The average increase and range by which electrical conductivity changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 173.7 with a range of 159.0 to 189.0 umhos/cm;

b. pH 8.0: average increase was 264.8 with a range of 235.0 to 295.0 umhos/cm; and

c. pH 8.5: average increase was 607.3 with a range of 571.0 to 661.0 umhos/cm.

Unlike the copper results, the increases in electrical conductivity of each setting were greater. This is attributed in having to add sodium hydroxide more periodically than was required for the copper experiments in maintaining the desired pH settings.

Figure C.2.6.1.1
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Copper At Different pH Settings

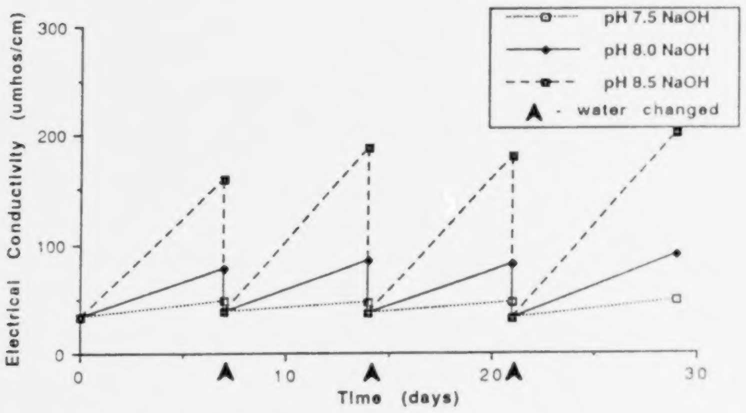
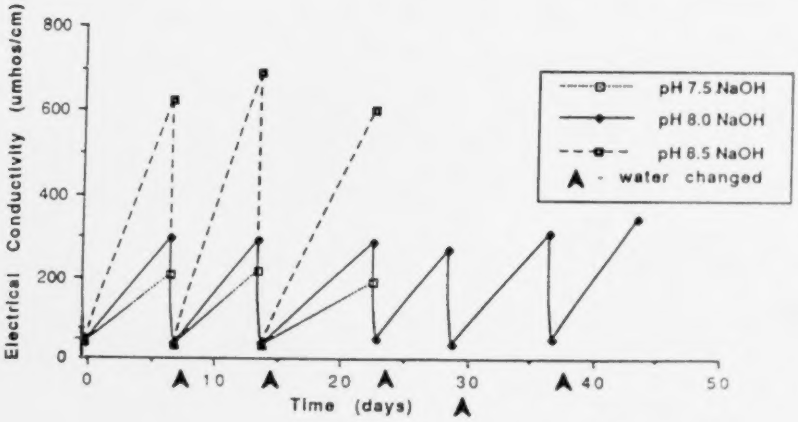


Figure C.2.6.2.1
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



C.2.7 Iron Concentration

C.2.7.1 Ductile Iron Experiments

Figure C.2.7.1.1 shows the weekly changes in iron concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The average increase and range by which the iron concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 3.18 mg/L with a range of 1.29 to 4.21 mg/L as total Fe;
b. pH 8.0: average increase was 0.85 mg/L with a range of 0.02 to 2.28 mg/L as total Fe; and
c. pH 8.5: average increase was 0.84 mg/L with a range of 0.60 to 1.01 mg/l as total Fe.

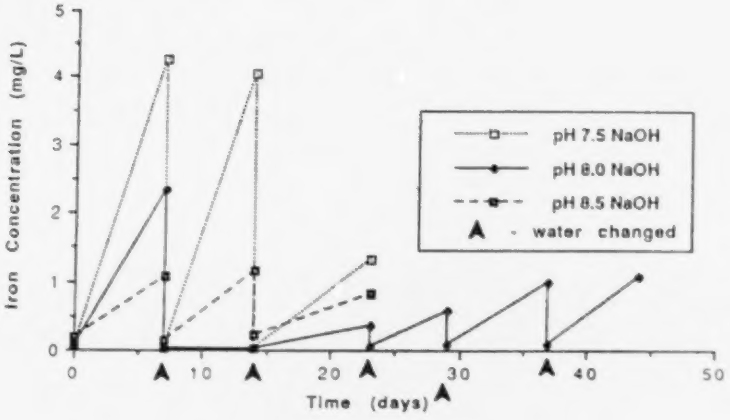
The increases in iron concentration of each setting were initially high, and later decreased with time. This is attributed to the removal of coupons and from a reduction in corrosion with time. The tendency of the data indicates that less iron wass available in solution with increasing pH even though the corrosion rates increased with pH. This suggests that scale formation on the surfaces of coupons was greater and less protective than that formed for the lower pH's.

C.2.8 Magnesium Concentration

C.2.8.1 Copper Experiments

Figure C.2.8.1.1 shows the weekly changes in magnesium concentration of the experimental waters, for the immersion of copper at different pH

Figure C.2.7.1.1
Weekly Changes in Iron Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



settings. The magnesium concentration of each setting increased slightly from liquid losses due to evaporation. The average increase and range by which the magnesium concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 0.14 mg/L with a range of 0.09 to 0.22 mg/L as Mg^{2+};
b. pH 8.0: average increase was 0.10 mg/L with a range of 0.04 to 0.14 mg/L as Mg^{2+}; and
c. pH 8.5: average increase was 0.08 mg/L with a range of 0.02 to 0.17 mg/L as Mg^{2+}.

C.2.8.2 Ductile Iron Experiments

Figure C.2.8.2.1 shows the weekly changes in magnesium concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The magnesium concentrations decreased slightly and the tendency was that the higher the pH, the greater the decrease. The average decrease and range by which the magnesium concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average change was -0.19 mg/L with a range of -0.41 to -0.31 mg/L as Mg^{2+};
b. pH 8.0: average change was -0.20 mg/L with a range of -0.41 to -0.04 mg/L as Mg^{2+}; and
c. pH 8.5: average change was -0.41 mg/L with a range of -0.50 to -0.30 mg/L as Mg^{2+}.

Figure C.2.8.1.1

Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

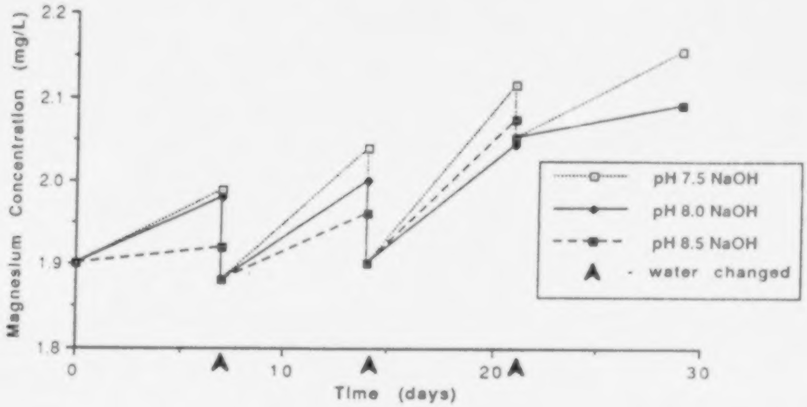
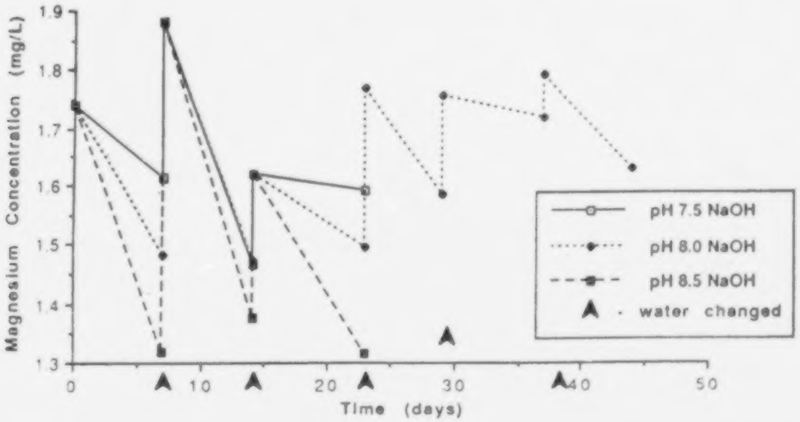


Figure C.2.8.2.1

Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



C.2.9 pH

C.2.9.1 Copper Experiments

Figures C.2.9.1.1, C.2.9.1.2, and C.2.9.1.3 show the daily changes in pH of the experimental waters, for the immersion of copper at different pH settings using sodium hydroxide for pH adjustment.

C.2.9.2 Ductile Iron Experiments

Figures C.2.9.2.1, C.2.9.2.2 and C.2.9.2.3 show the daily changes in pH of the experimental waters, for the immersion of ductile iron at different pH settings using sodium hydroxide for pH adjustment.

C.2.10 Silicate Concentration

C.2.10.1 Copper Experiments

Figure C.2.10.1.1 shows the weekly changes in silicate concentration of the experimental waters, for the immersion of copper at different pH settings. The silicate concentration of each setting, increased slightly from liquid losses due to evaporation for a weekly liquid retention time. The average increase and range by which the silicate concentration changed for each pH setting for a weekly retention time was:

a. pH 7.5: average increase was 0.06 mg/L with a range of -0.01 to 0.14 mg/L as Si;
b. pH 8.0: average increase was 0.13 mg/L with a range of 0.04 to 0.23 mg/L as Si; and
c. pH 8.5: average increase was 0.09 mg/L with a range of 0.02 to 0.18 mg/L as Si.

Figure C.2.9.1.1
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH Setting 7.5 Using Sodium Hydroxide

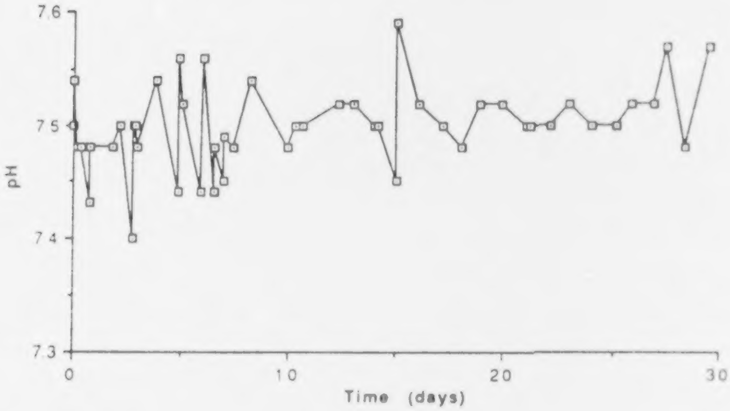


Figure C.2.9.1.2
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH Setting 8.0 Using Sodium Hydroxide

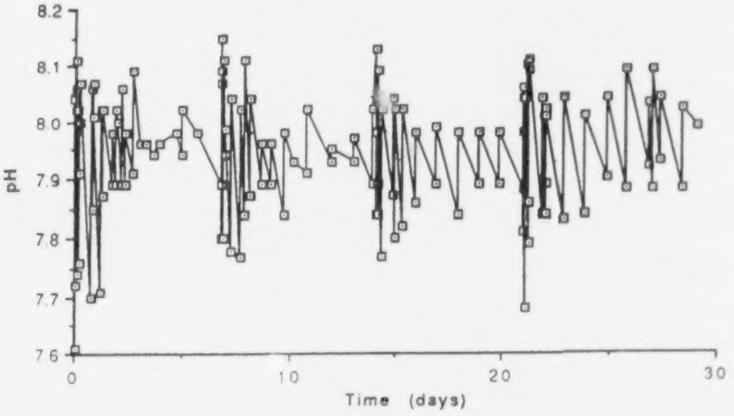


Figure C.2.9.1.3
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH Setting 8.5 Using Sodium Hydroxide

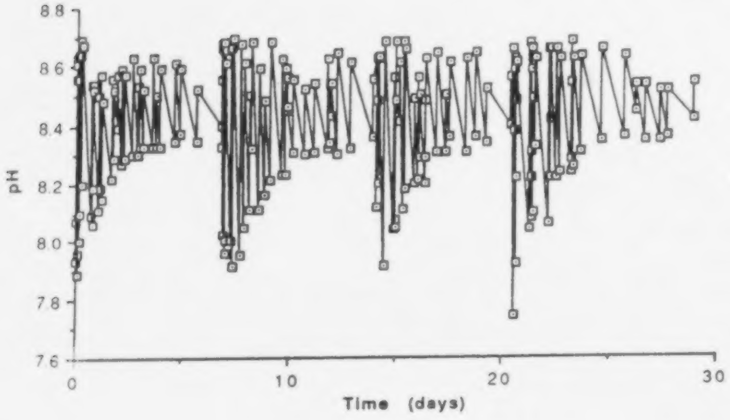


Figure C.2.9.2.1
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH Setting 7.5 Using Sodium Hydroxide

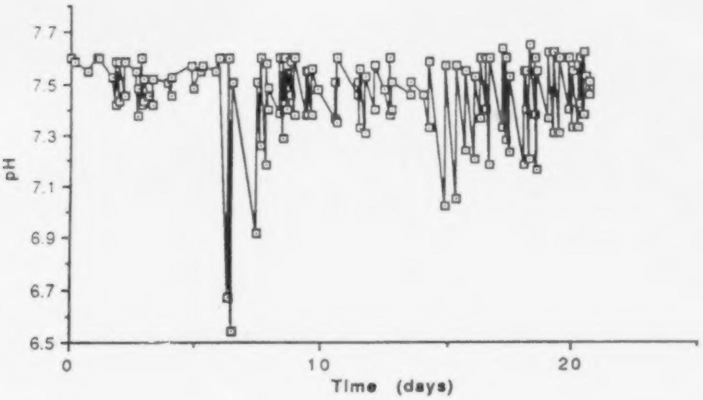


Figure C.2.9.2.2
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH Setting 8.0 Using Sodium Hydroxide

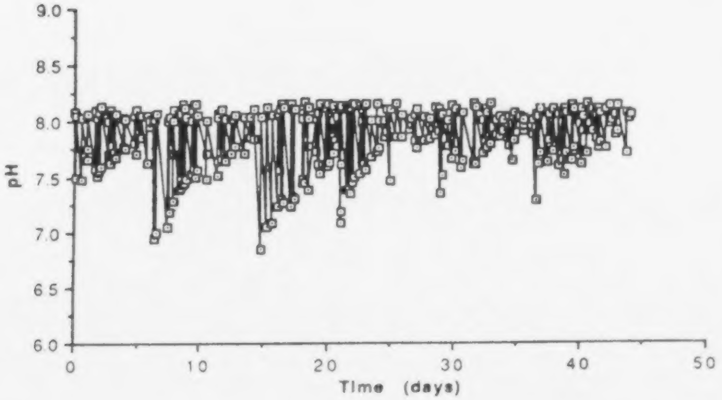
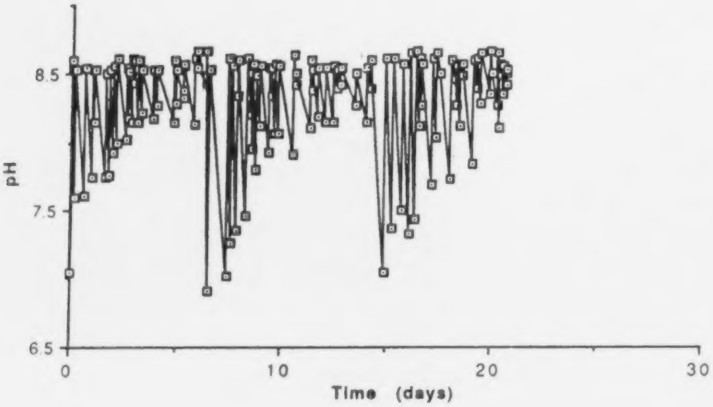


Figure C.2.9.2.3
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH Setting 8.5 Using Sodium Hydroxide



C.2.10.2 Ductile Iron Experiments

Figure C.2.10.2.1 shows the weekly changes in silicate concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The average increase and range by which the silicate concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 1.32 mg/L with a range of 1.02 to 1.65 mg/L as Si;

b. pH 8.0: average increase was 1.20 mg/L with a range of 0.74 to 1.76 mg/l as Si; and

c. pH 8.5: average increase was 0.84 mg/L with a range of 0.60 to 1.01 mg/L as Si.

The increases in silicate concentration are shown increasing with decreasing pH. Shown as well, are the increases of each setting as being much higher than for the copper results. This is attributed to ductile iron's chemical properties. Ductile iron has included in its chemical composition 2.5 to 2.6 percent silicate (AWWA, 1985). The release of silicate into solution, from corrosion, contributed to the water's increase in silicate concentration.

C.2.11 Sodium Concentration

C.2.11.1 Copper Experiments

Figure C.2.11.1.1 shows the weekly increases in sodium concentration of the experimental waters, for the immersion of copper from primarily adding sodium hydroxide to maintain the desired pH settings. The average increase and range by which the sodium concentration changed for each pH setting for a weekly liquid retention time was:

Figure C.2.10.1.1
Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

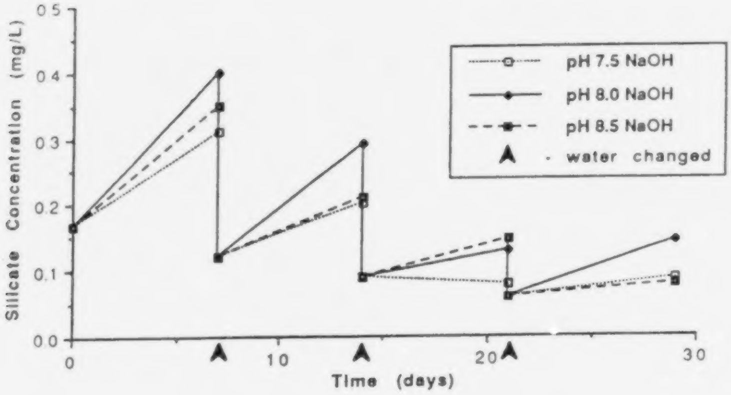
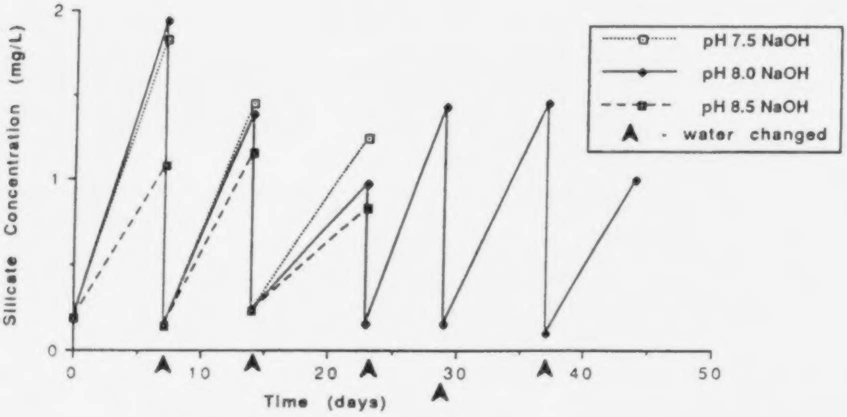


Figure C.2.10.2.1
Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



a. pH 7.5: the average increase was 3.16 mg/L with a range of 2.49 to 3.78 mg/L as Na^+;

b. pH 8.0: the average increase was 16.08 mg/L with a range of 14.46 to 17.80 mg/L as Na^+; and

c. pH 8.5: the average increase was 52.06 mg/L with a range of 47.03 to 58.96 mg/L as Na^+.

Lines are not drawn connecting the data points for each setting as unknown was rate by which the sodium concentration changed for the liquid's retention time.

C.2.11.2 Ductile Iron Experiments

Figure C.2.11.2.1 shows the weekly increases in sodium concentration of the experimental waters, for the immersion of ductile iron from primarily adding sodium hydroxide to maintain the desired pH settings. The average increase and range by which sodium concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5, average increase was 69.11 mg/L with a range of 58.29 to 81.92 mg/L as Na^+;

b. pH 8.0, average increase was 108.84 mg/L with a range of 98.31 to 120.64 mg/L as Na^+; and

c. pH 8.5, average increase was 224.40 mg/L with a range of 222.40 to 225.55 mg/L as Na^+.

Lines are not drawn connecting the data points for each setting as unknown was rate by which the sodium concentration changed for the liquid's retention time.

Figure C.2.11.1.1
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

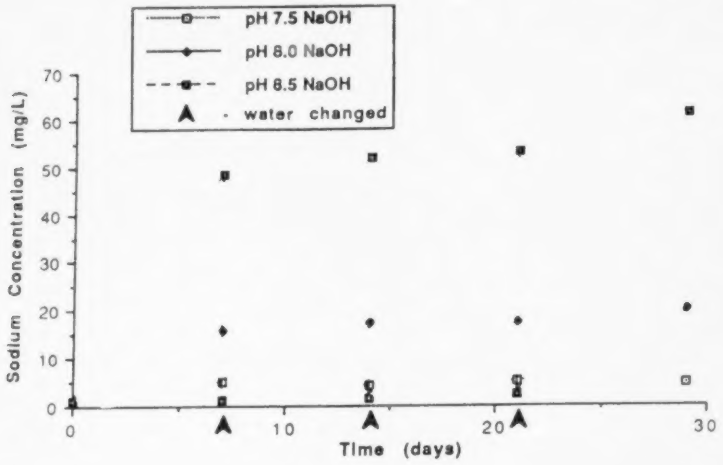
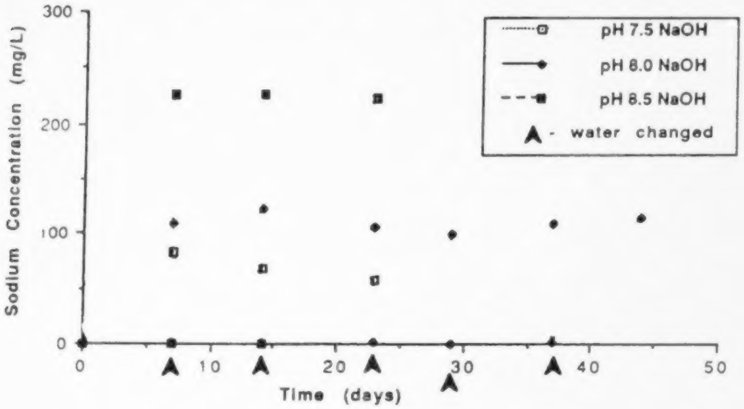


Figure C.2.11.2.1
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



C.2.12 Sulfate Concentration

C.2.12.1 Copper Experiments

Figure C.2.12.1.1 shows the weekly changes in sulfate concentration of the experimental waters, for the immersion of copper at different pH settings. The average increase and range by which the sulfate concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5, average increase was 0.39 mg/L with a range of 0.07 to 0.52 mg/L as SO_4^{2-};

b. pH 8.0, average increase was 0.28 mg/L with a range of -0.01 to 0.64 mg/L as SO_4^{2-}; and

c. pH 8.5, average increase was 0.32 mg/L with a range of 0.12 to 0.60 mg/L as SO_4^{2-}.

The sulfate concentration of each setting increased slightly from liquid losses due to evaporation for a weekly liquid retention time.

C.2.12.2 Ductile Iron Experiments

Figure C.2.12.2.1 shows the weekly changes in sulfate concentration of the experimental waters, for the immersion of ductile iron at different pH settings. The average decrease and range by which the sulfate concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5, average change was -1.56 mg/L with a range of -2.15 to -1.23 mg/L as SO_4^{2-};

b. pH 8.0, average change was -1.29 mg/L with a range of -3.15 to -0.64 mg/L as SO_4^{2-}; and

Figure C.2.12.1.1
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

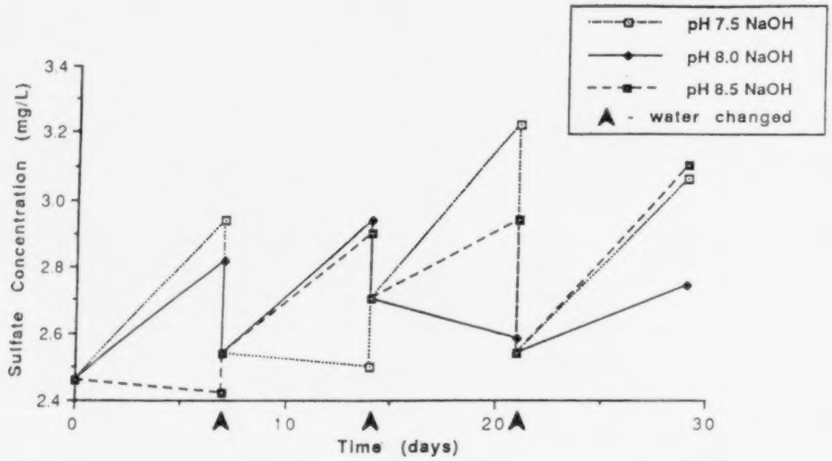
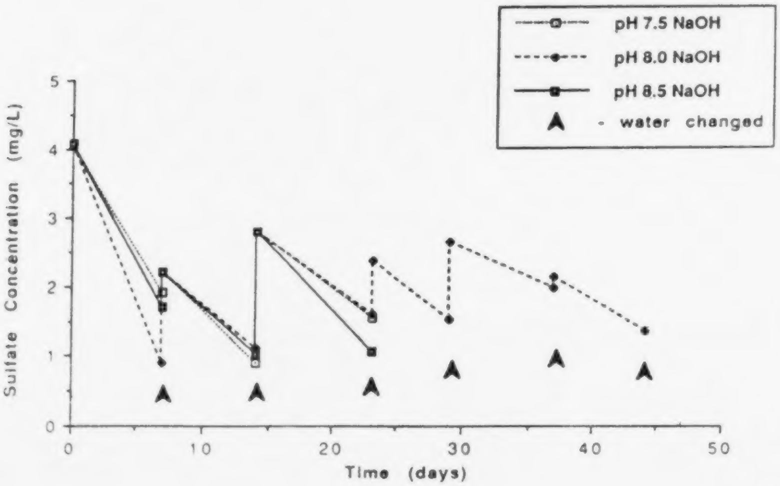


Figure C.2.12.2.1
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



c. pH 8.5, average change was -1.75 mg/L with a range of -2.35 to -1.19 mg/L as SO_4^{2-}.

C.2.13 Temperature

The temperatures at which the experiments were performed, ranged from 5 to 7 °C.

C.2.14 Total Hardness Concentration

C.2.14.1 Copper Experiments

Figure C.2.14.1.1 shows the weekly changes in total hardness concentration of the experimental waters, for the immersion of copper at different pH settings. The total hardness concentration of each setting increased slightly for the weekly retention times from liquid losses due to evaporation. The average increase and range by which the total hardness concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 1.3 mg/L with a range of 0.0 to 1.8 mg/L as $CaCO_3$;

b. pH 8.0: average increase was 1.1 mg/L with a range of 0.2 to 2.2 mg/L as $CaCO_3$; and

c. pH 8.5: average increase was 1.6 mg/L with a range of 0.6 to 2.6 mg/L as $CaCO_3$.

The waters were greatly undersaturated with respect to $CaCO_3$, that pH adjustment between the range of 7.5 to 8.5 was, by itself, not sufficient to precipitate $CaCO_3$. Copper when exposed alone, does not generate the cell activity required to cause $CaCO_3$ to precipitate locally onto its surface. Only when it functions as the cathode of a galvanic coupling, is it coated with $CaCO_3$.

C.2.14.2 Ductile Iron Experiments

Figure C.2.14.2.1 shows the weekly changes in the total hardness concentrations of the experimental waters, for the immersion of ductile iron at different pH settings. The average change and range by which the total hardness concentration changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 3.1 mg/L with a range of -1.0 to 10.2 mg/L as $CaCO_3$;

b. pH 8.0: average change was -1.5 mg/L with a range of -8.5 to 2.6 mg/L as $CaCO_3$; and

c. pH 8.5: average increase was 0.6 mg/L with a range of -1.3 to 4.0 mg/L as $CaCO_3$.

The total hardness concentration of each setting increased slightly for a weekly liquid retention time. Shown, are the increases in hardness concentration as decreasing with increasing pH.

C.2.15 Turbidity

C.2.15.1 Copper Experiments

Figure C.2.15.1.1 shows the weekly changes in turbidity of the experimental waters, for the immersion of copper at different pH settings. The average increase and range by which the turbidity changed for each pH setting for a weekly liquid retention time was:

Figure C.2.14.1.1
Weekly Changes in Total Hardness Concentration of the Experimental Waters for the Immersion of Copper At Different pH Settings

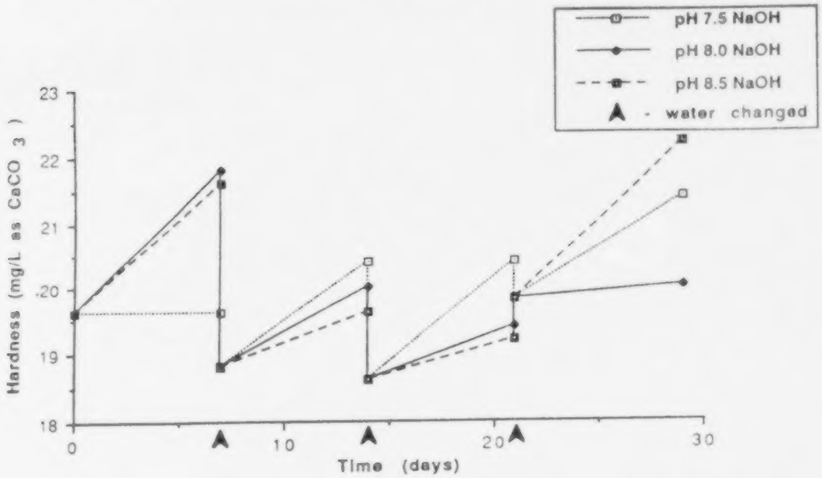
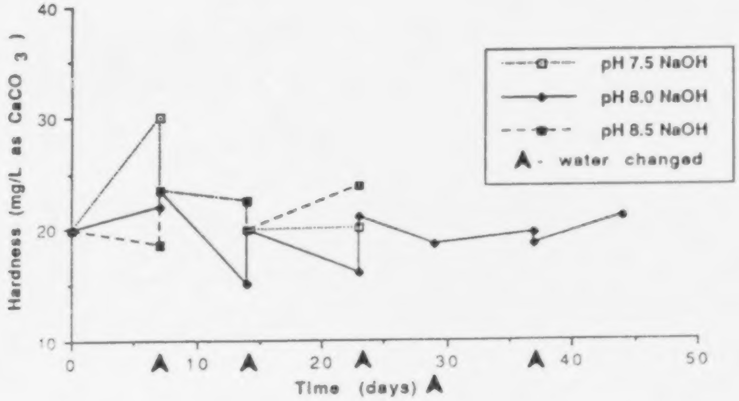


Figure C.2.14.2.1
Weekly Changes in Total Hardness Concentration of the Experimental Waters for the Immersion of Ductile Iron At Different pH Settings



a. pH 7.5: average increase was 0.7 with a range of 0.1 to 1.3 NTU;
b. pH 8.0: average increase was 0.4 with a range of -0.4 to 1.1 NTU; and
c. pH 8.5: average increase was 0.1 with a range of -0.5 to 0.6 NTU.

The increases in turbidity are shown decreasing with increasing pH. The increases are the contribution of primarily copper corrosion and, to a lesser extent, from liquid losses due to evaporation.

C.2.15.2 Ductile Iron Experiments

Figure C.2.15.2.1 shows the weekly changes in turbidity of the experimental waters, for the immersion of ductile iron at different pH settings. The average increase and range by which the turbidity changed for each pH setting for a weekly liquid retention time was:

a. pH 7.5: average increase was 8.6 with a range of 4.3 to 11.6 NTU;
b. pH 8.0: average increase was 5.1 with a range of 2.1 to 9.7 NTU; and
c. pH 8.5: average increase was 7.6 with a range of 3.9 to 10.0 NTU.

`Turbidity increases of each setting were generally the same. The increases were initially high and later decreased with exposure time. This is attributed to the removal of coupons and to a reduction in ductile iron corrosion with time.

Figure C.2.15.1.1
Weekly Changes in Turbidity of the Experimental Waters
for the Immersion of Copper At Different pH Settings

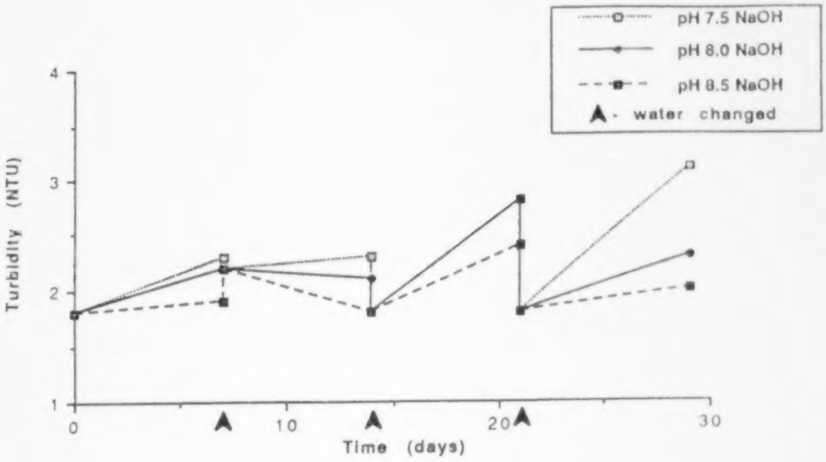
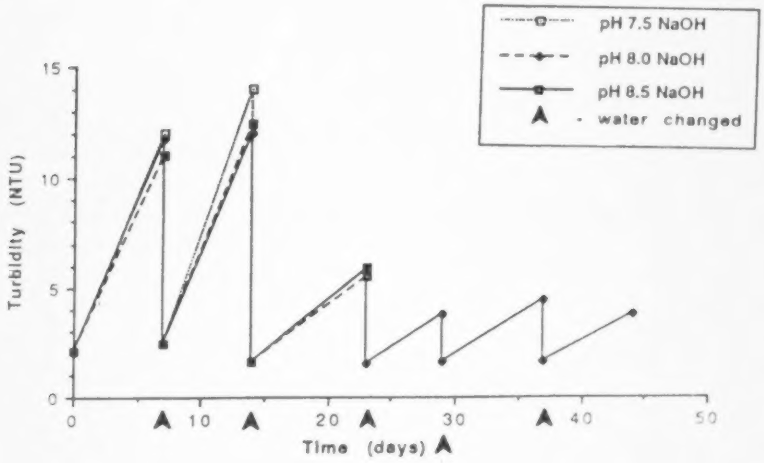


Figure C.2.15.2.1
Weekly Changes in Turbidity of the Experimental Waters
for the Immersion of Ductile Iron At Different pH Settings



Appendix D

Detailed Summary of the Water Quality Changes for the Lime Tests.

The following is a detailed summary of the water quality changes for each setting of the lime experiments. Detailed are the weakly changes in water quality throughout the duration of each corrosion test conducted using the inhibitors, lime, carbon dioxide, and sodium hydroxide.

D.1 Experimental Schedule

D.1.1 Copper Experiments

Figures D.1.1.1, D.1.1.2, D.1.1.3, D.1.1.4, and D.1.1.5 are the experimental schedules for the removal of copper coupons at different pH and hardness settings. Sample sets consisted of 2 to 4 coupons and were removed weekly. The duration of the experiments was approximately 30 days.

D.1.2 Ductile Iron Experiments

Figures D.1.2.1, D.1.2.2, D.1.2.3, D.1.2.4, and D.1.2.5 are the experimental schedules for the removal of ductile iron coupons at different pH and hardness settings. Sample sets consisted to 2 to 3 coupons and were removed weekly. The duration of the experiments varied between 27 to 46 days.

D.2 Laboratory Water Characteristics

Throughout the experiments, several water quality parameters were monitored on a weekly basis. These water parameters were measured prior to the immersion of coupons and again when changing the water on a weekly basis. Presented, are the weekly variations in water quality for the immersion of ductile iron and copper coupons at different pH and hardness settings.

Figure D.1.1.1
Experimental Schedule: pH 7.5 and Hardness
25 mg/L as CaCO3

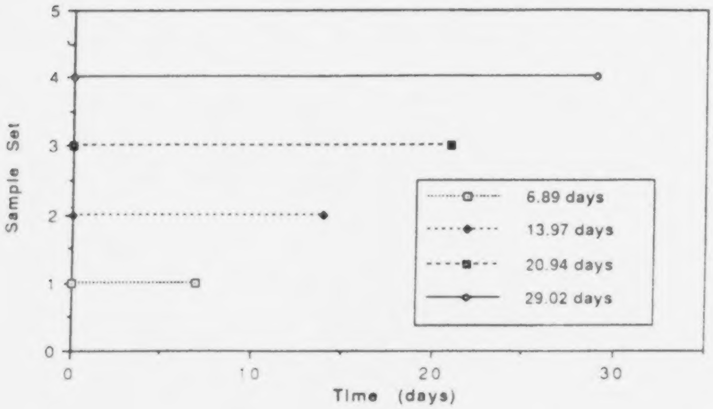


Figure D.1.1.2
Experimental Schedule: pH 8.5 and Hardness
25 mg/L as CaCO3

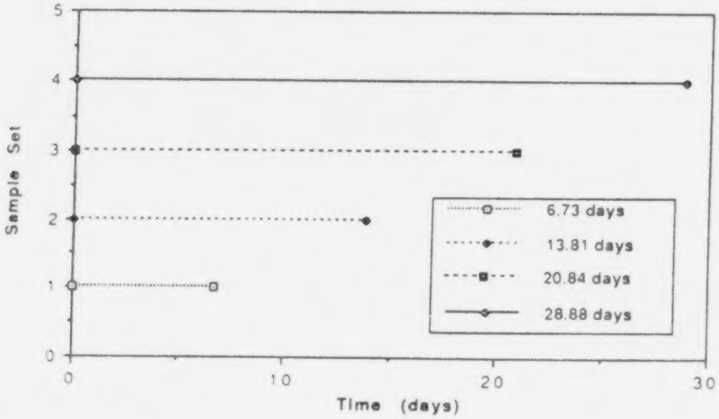


Figure D.1.1.3
Experimental Schedule: pH 7.5 and Hardness
75 mg/L as $CaCO_3$

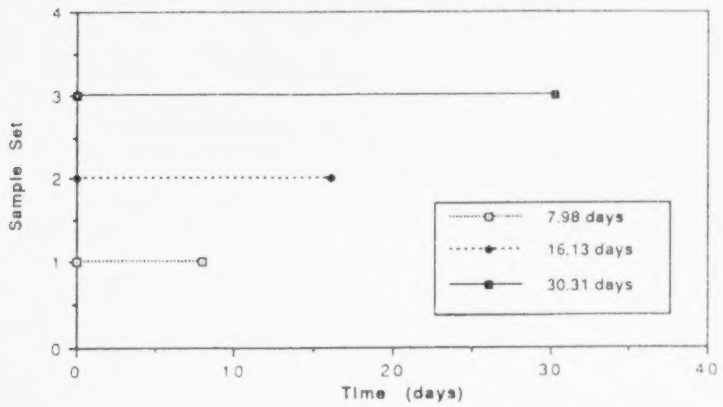


Figure D.1.1.4
Experimental Schedule: pH 8.5 and Hardness
75 mg/L as $CaCO_3$

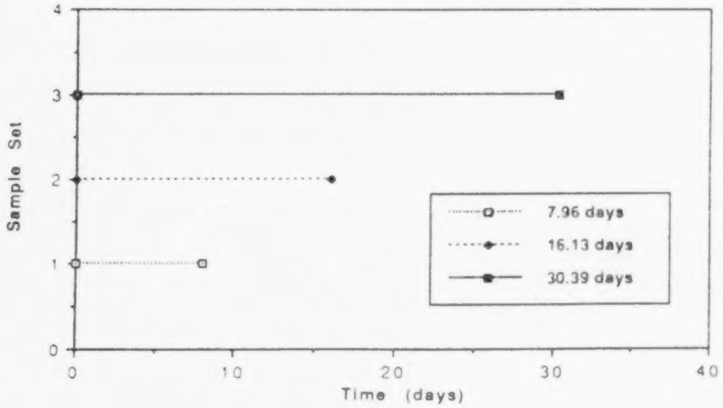


Figure D.1.1.5
Experimental Schedule: pH 8.0 and Hardness
50 mg/L as $CaCO_3$

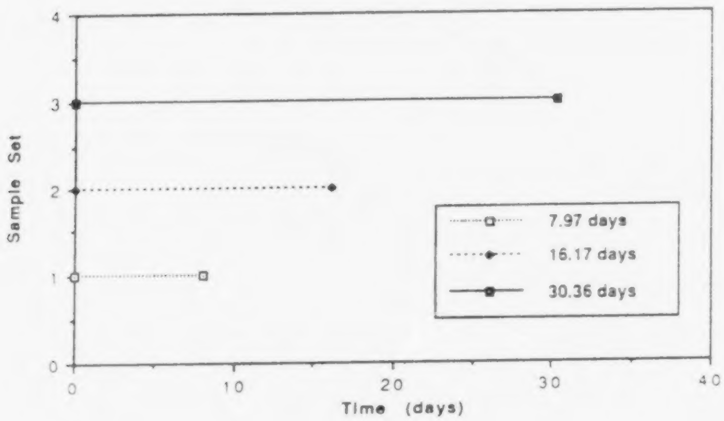


Figure D.1.2.1
Experimental Schedule: pH 7.5 and Hardness 25 mg/L as $CaCO_3$

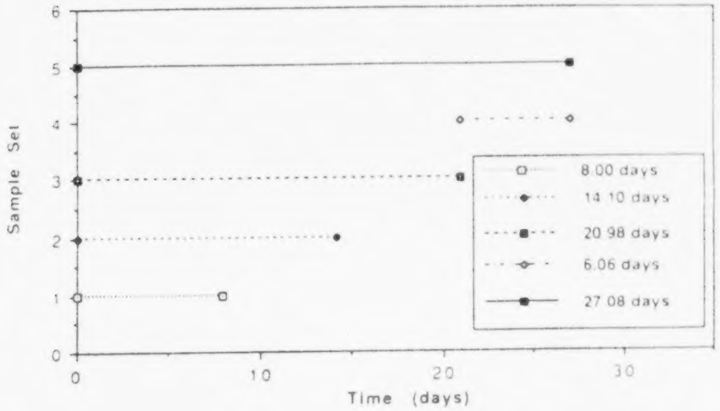


Figure D.1.2.2
Experimental Schedule: pH 8.5 and Hardness 25 mg/L as $CaCO_3$

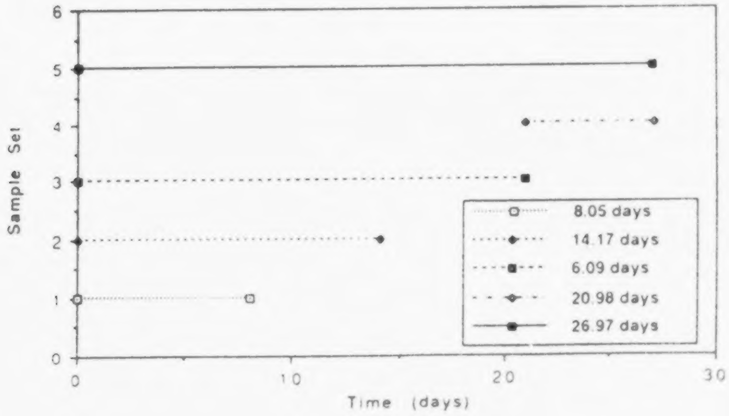


Figure D.1.2.3
Experimental Schedule: pH 8.0 and Hardness
50 mg/L as CaCO3

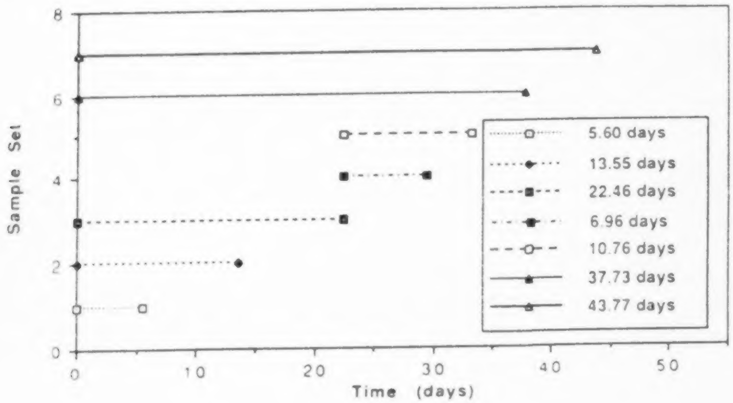


Figure D.1.1.4
Experimental Schedule: pH 8.5 and Hardness
75 mg/L as CaCO3

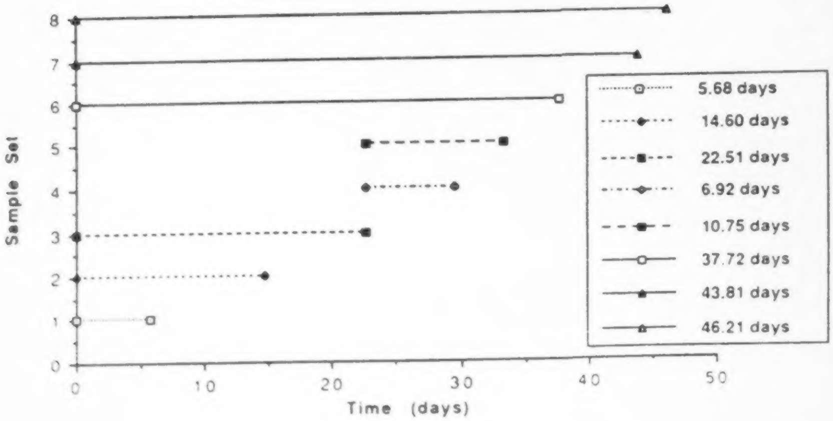
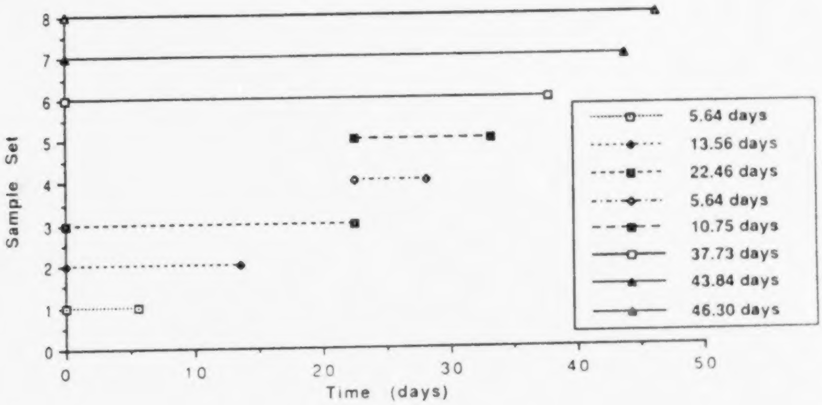


Figure D.1.1.5
Experimental Schedule: pH 7.5 and Hardness
75 mg/L as CaCO3



D.2.1 Alkalinity

D.2.1.1 Copper Experiments

Figures D.2.1.1.1 and D.2.1.1.2 show the weekly changes in alkalinity of the experimental waters, for the immersion of copper at different pH and hardness settings. The alkalinity increased from sodium hydroxide and lime addition. The average increase and range by which the alkalinity changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 109.4 mg/L with a range of 91.8 to 113.4 mg/L as $CaCO_3$;

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 242.9 with a range of 215.4 to 257.8 mg/L as $CaCO_3$;

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 507.5 mg/L with a range of 422.4 to 584.5 mg/L as $CaCO_3$;

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 5.5 mg/L with a range of 5.1 to 5.7 mg/L as $CaCO_3$; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 108.0 mg/L with a range of 99.7 to 121.5 mg/L as $CaCO_3$.

The changes in alkalinity increased with increasing pH. The most significant changes in water quality occurred primarily from sodium hydroxide addition.

D.2.1.2 Ductile Iron Experiments

Figures D.2.1.2.1 and D.2.1.2.2 show the weekly changes in alkalinity of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. The average increase and range by which the alkalinity changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 122.0 mg/L with a range of 73.9 to 177.8 mg/L as $CaCO_3$;
b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 212.8 mg/L with a range of 155.9 to 263.2 mg/L as $CaCO_3$;
c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 374.3 mg/L with a range of 280.7 to 482.3 mg/L as $CaCO_3$;
d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 94.7 with a range of 68.4 to 131.0 mg/L as $CaCO_3$; and
e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 313.5 with a range of 97.8 to 408.6 mg/L as $CaCO_3$.

D.2.2 Chloride Concentration

D.2.2.1 Copper Experiments

Figures D.2.2.1.1 and D.2.2.1.2 show the weekly changes in chloride concentration of the experimental waters for the immersion of copper at

Figures D.2.1.1.1 & D.2.1.1.2
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

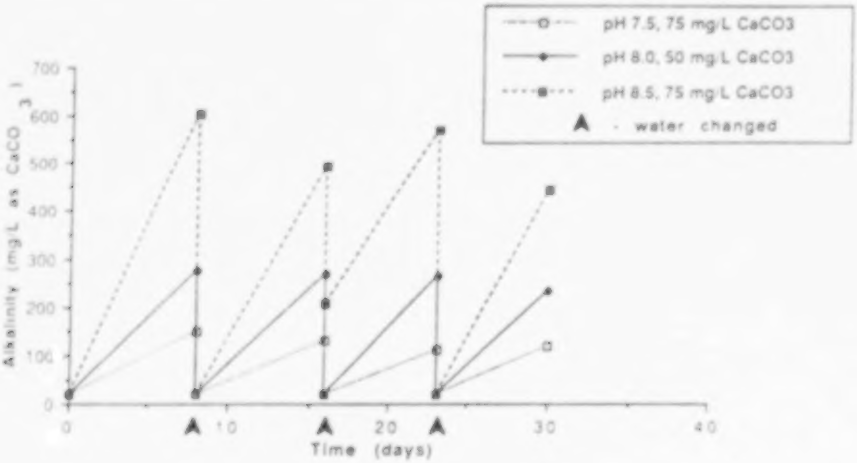
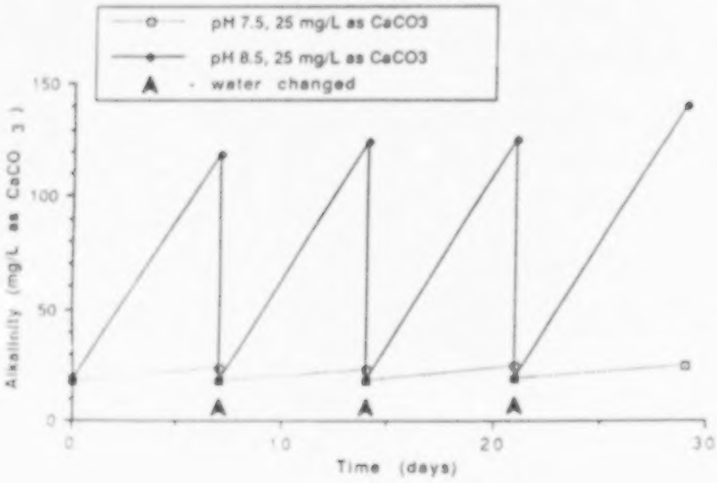


Figure D.2.1.1.2



Figures D.2.1.2.1 & D.2.1.2.2
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

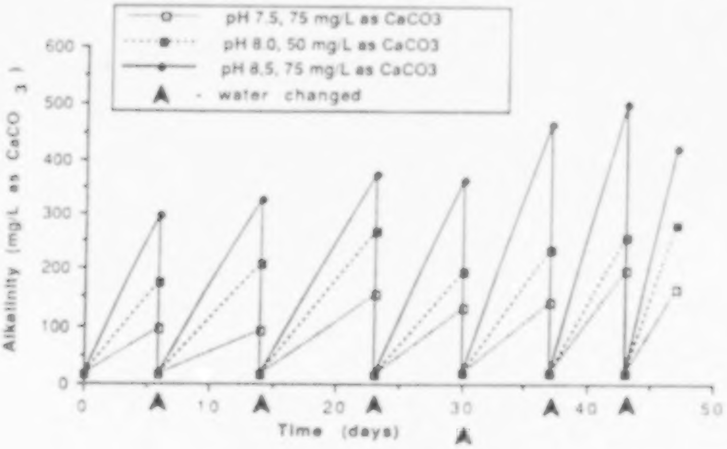
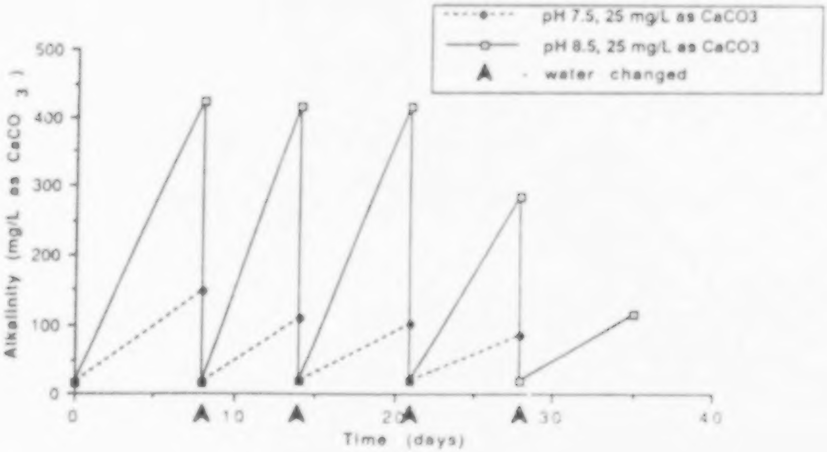


Figure D.2.1.2.2



different pH and hardness settings. The chloride concentrations increased from chlorination. The average increase and range by which the chloride concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 4.17 mg/L with a range of 1.76 to 6.87 mg/L as Cl^-;
b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 2.33 mg/L with a range of 1.99 to 2.55 mg/L as Cl^-;
c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 3.67 mg/L with a range of 2.67 to 5.48 mg/L as Cl^-;
d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 5.19 mg/L with a range of 3.12 to 10.26 mg/L as Cl^-; and
e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 5.78 mg/L with a range of 3.00 to 12.66 mg/L as Cl^-.

D.2.2.2 Ductile Iron Experiments

Figures D.2.2.2.1 and D.2.2.2.2 show the weekly changes in chloride concentration of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. The chloride concentrations increased from chlorination. The average increase and range by which the chloride concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 4.02 mg/L with a range of 2.53 to 9.81 mg/L as Cl^-;

Figures D.2.2.1.1 & D.2.2.1.2
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

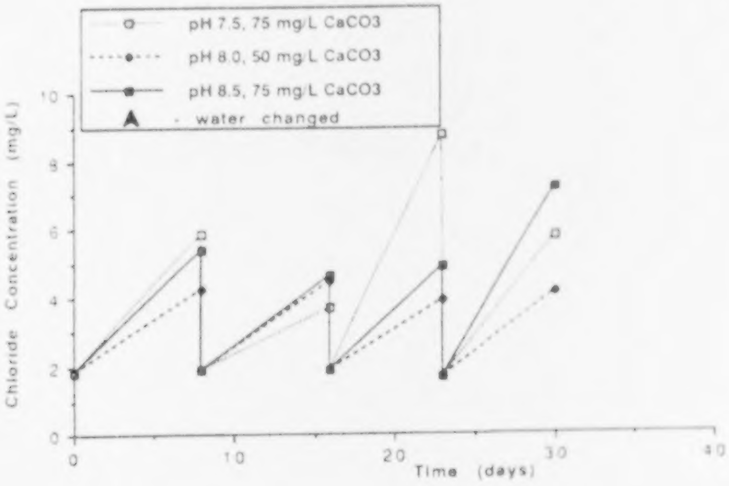
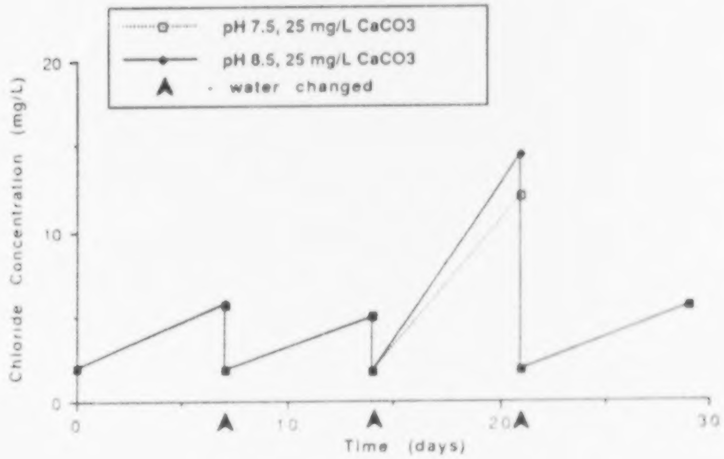


Figure D.2.2.1.2



b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 5.12 mg/L with a range of 1.91 to 10.91 mg/L as Cl^-;

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 5.54 mg/L with a range of 2.28 to 10.98 mg/L as Cl^-;

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 9.11 mg/L with a range of 2.15 to 15.62 mg/L as Cl^-; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 6.33 mg/L with a range of 1.05 to 10.28 mg/L as Cl^-.

The chloride and alkalinity of each setting increased from chemical additions. The increases in alkalinity of each setting will have greatly reduced chloride's effect for influencing ductile iron corrosion. Not known, however, is what the chloride concentration was immediately after chlorination.

D.2.3 Copper Concentration

D.2.3.1 Copper Experiments

Figures D.2.3.1.1 and D.2.3.1.2 show the weekly changes in copper concentration of the experimental waters, for the immersion of copper at different pH and hardness settings. The average increase and range by which the copper concentration changed for each setting for a weekly liquid retention time was:

Figures D.2.2.2.1 & D.2.2.2.2
Weekly Changes in Chloride Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

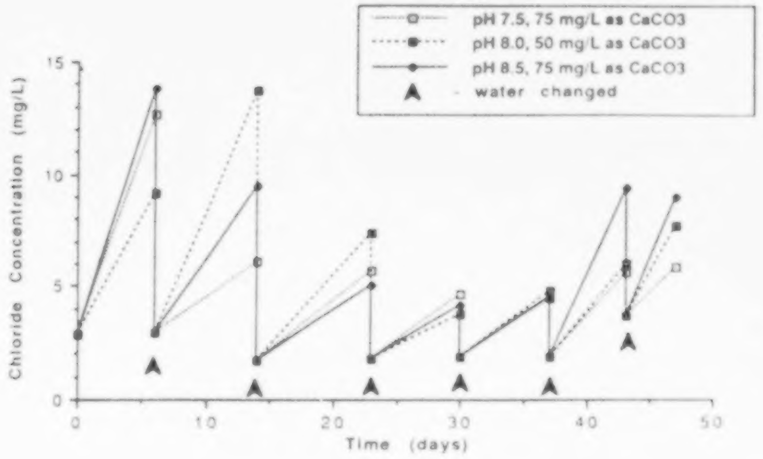
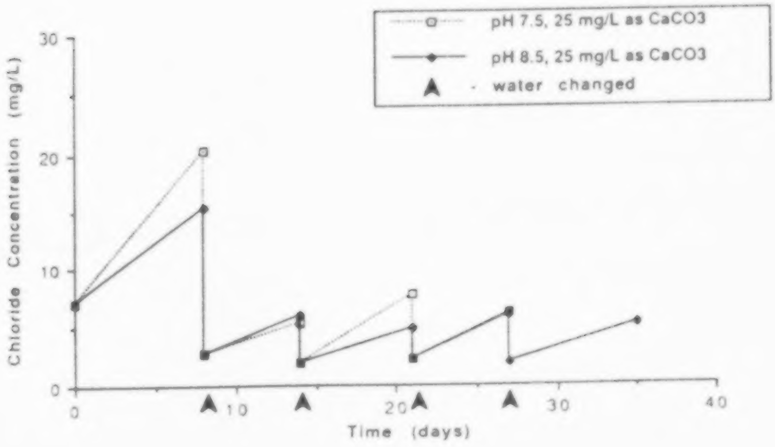


Figure D.2.2.2.2



a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 0.67 mg/L with a range of 0.18 to 1.66 mg/L as Cu^{2+};

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 0.50 mg/L with a range of 0.12 to 1.04 mg/L as Cu^{2+};

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 0.33 mg/L with a range of 0.22 to 0.58 mg/L as Cu^{2+};

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 1.17 mg/L with a range of 0.77 to 1.43 mg/L as Cu^{2+}; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 0.74 mg/L with a range of 0.53 to 0.85 mg/L as Cu^{2+}.

D.2.4 Dissolved Oxygen Concentration

D.2.4.1 Copper Experiments

Figures D.2.4.1.1 and D.2.4.1.2 show the dissolved oxygen concentrations as measured when changing the experimental waters on a weekly basis, for the immersion of copper at different pH and hardness settings. The dissolved oxygen concentrations of the experimental waters were kept relatively constant from the continual aeration of the waters. The average and range by which the dissolve oxygen concentration varied for each setting was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average was 11.62 with a range of 11.55 to 11.68 mg/L as O_2;

Figures D.2.3.1.1 & D.2.3.1.2
Weekly Changes in Copper Concentration of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

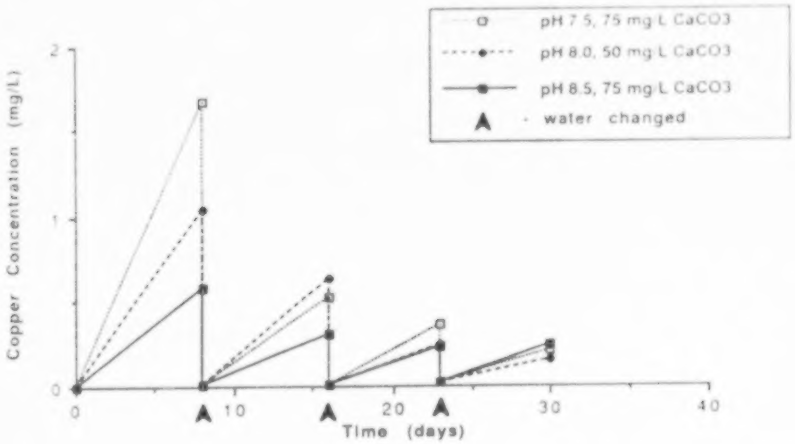
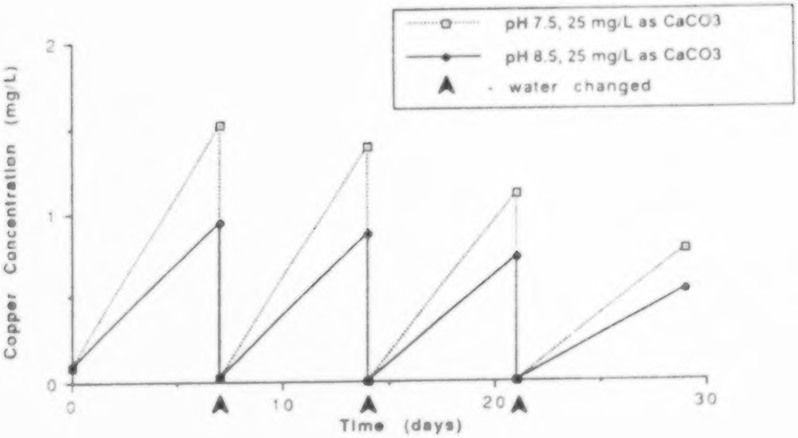


Figure D.2.3.1.2



b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average
was 11.63 with a range of 11.55 to 11.67 mg/L as O_2;
c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average
was 11.64 with a range of 11.62 to 11.68 mg/L as O_2;
d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average
was 11.61 with a range of 11.58 to 11.64 mg/L as O_2; and
e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average
was 11.64 with a range of 11.60 to 11.66 mg/L as O_2.

D.2.4.2 Ductile Iron Experiments

Figures D.2.4.2.1 and D.2.4.2.2 show the dissolved oxygen concentrations as measured when changing the experimental waters on a weekly basis, for the immersion of ductile iron at different pH and hardness settings. The dissolved oxygen concentrations of the experimental waters were kept relatively constant from the continual aeration of the waters. The average and range by which the dissolve oxygen concentration varied for each setting was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average
was 11.28 with a range of 11.25 to 11.32 mg/L as O_2;
b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average
was 11.24 with a range of 11.20 to 11.28 mg/L as O_2;
c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average
was 11.24 with a range of 11.18 to 11.30 mg/L as O_2;
d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average
was 11.24 with a range of 11.20 to 11.26 mg/L as O_2; and

Figures D.2.4.1.1 & D.2.4.1.2
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

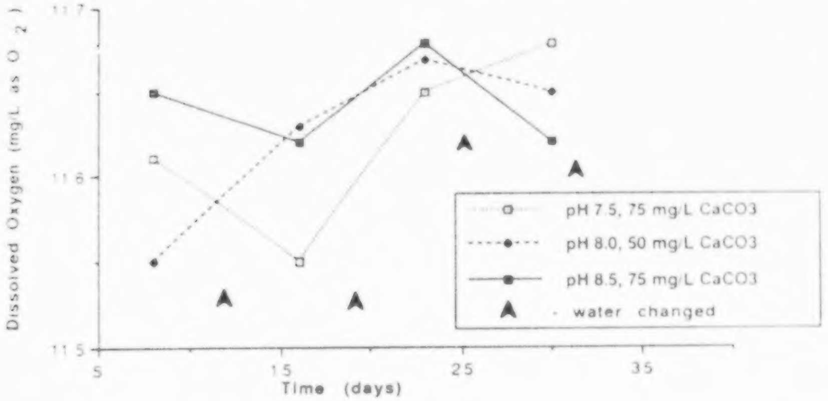
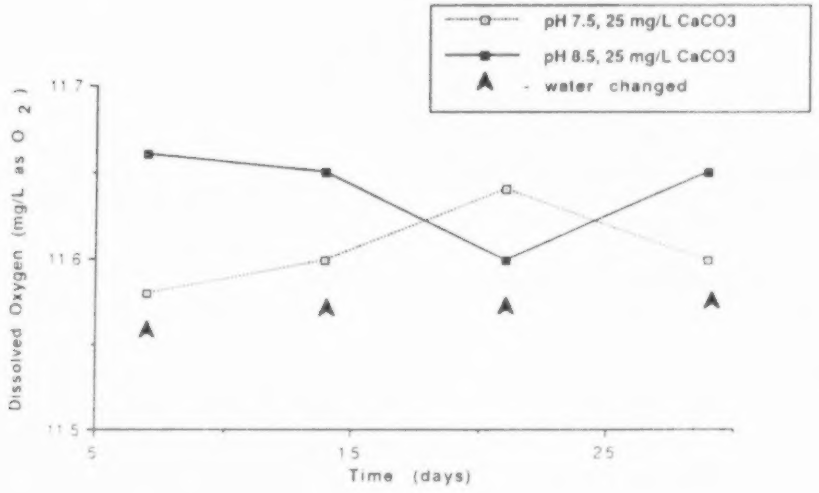


Figure D.2.4.1.2



Figures D.2.4.2.1 & D.2.4.2.2
Weekly Variations in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

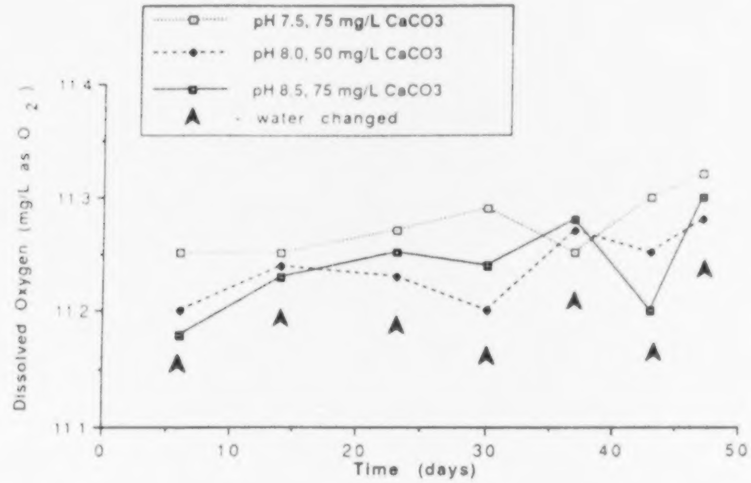
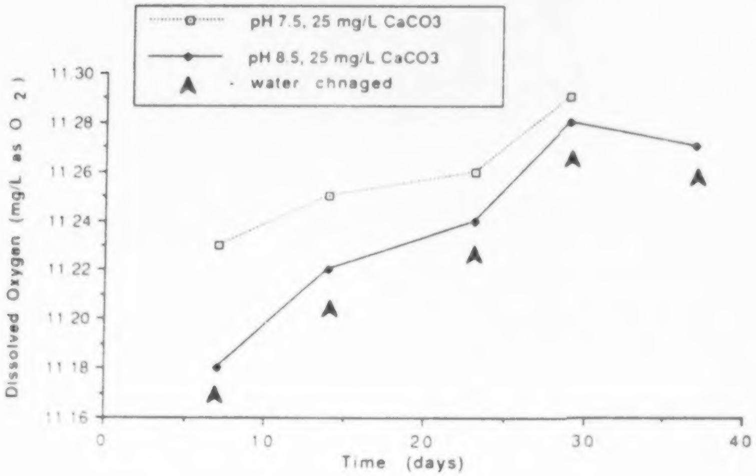


Figure D.2.4.2.2



e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average
was 11.20 with a range of 11.15 to 11.24 mg/L as O_2.

D.2.5 Electrical Conductivity

D.2.5.1 Copper Experiments

Figures D.2.5.1.1 and D.2.5.1.2 show the weekly changes in electrical conductivity of the experimental waters, for the immersion of copper at different pH and hardness settings. The electrical conductivities increased from both chemical addition and from corrosion. The average increase and range by which the electrical conductivity for each setting changed for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average
increase was 146.8 with a range of 117.0 to 155.0 umhos/cm;
b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average
increase was 323.8 with a range of 252.0 to 375.0 umhos/cm;
c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average
increase was 730.5 with a range of 532.0 to 885.0 umhos/cm;
d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average
increase was 16.5 with a range of 15.0 to 18.0 umhos/cm; and
e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average
increase was 149.0 with a range of 125.0 to 169.0 umhos/cm.

D.2.5.2 Ductile Iron Experiments

Figures D.2.5.2.1 and D.2.5.2.2 show the weekly changes in electrical conductivity for the immersion of ductile iron at different pH and hardness settings. Similarly, the electrical conductivities increased from chemical

Figures D.2.5.1.1 & D.2.5.1.2
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

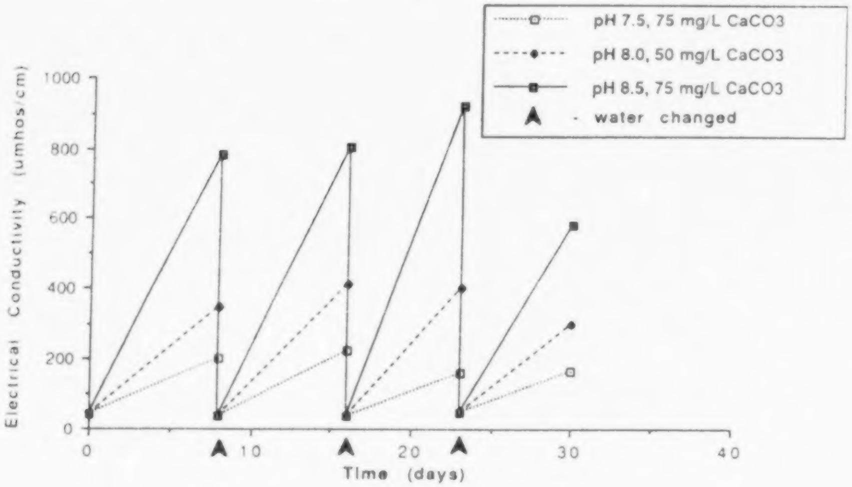
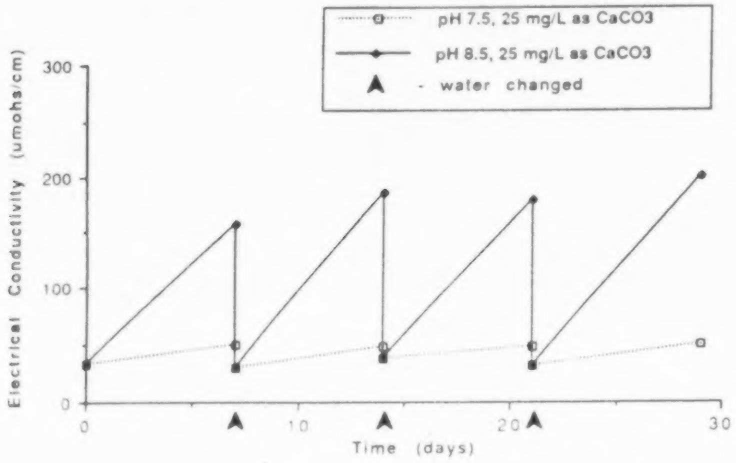


Figure D.2.5.1.2



addition and from corrosion. The average increase and range by which the electrical conductivity changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 201.1 with a range of 120.0 to 246.0 umhos/cm;
b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 293.3 with a range of 197.0 to 363.0 umhos/cm;
c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 586.3 with a range of 402.0 to 775.0 umhos/cm;
d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 123.5 with a range of 44.0 to 183.0 umhos/cm; and
e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 459.0 with a range of 149.0 to 593.0 umhos/cm.

D.2.6 Iron Concentration

D.2.6.1 Ductile Iron Experiments

Figures D.2.6.1.1 and D.2.6.1.2 show the weekly changes in iron concentration of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. The increases in iron concentration were initially high and later decreased with time. This is attributed to a reduction in corrosion with time and the removal of coupons. The average increase and range by which the iron concentration changed for setting for a weekly liquid retention time was:

Figures D.2.5.2.1 & D.2.5.2.2
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

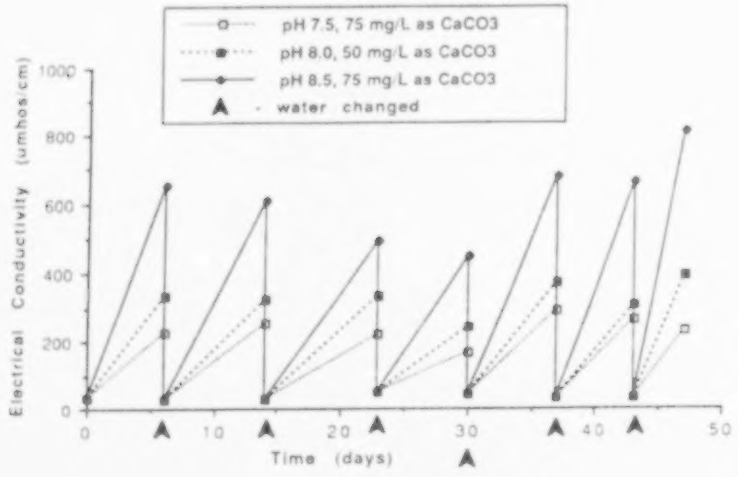
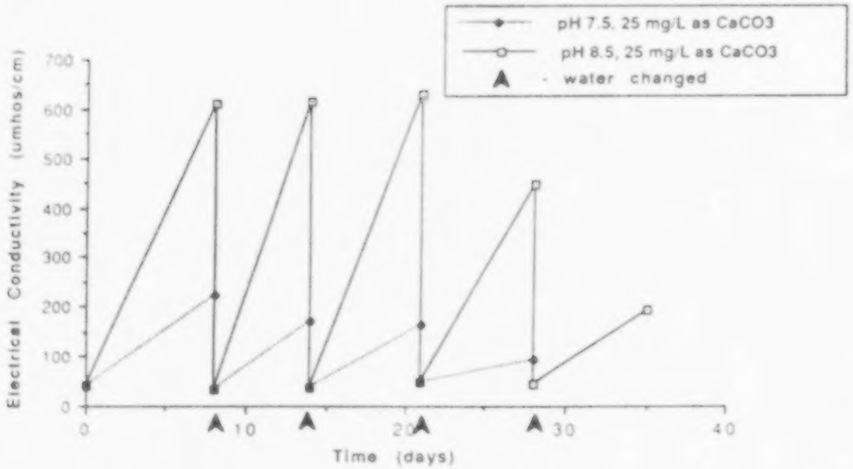


Figure D.2.5.2.2



a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average
increase was 2.36 mg/L with a range of -0.09 to 8.02
mg/L as total iron;
b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average
increase was 1.05 mg/L with a range of 0.01 to 3.41 mg/L as total iron;
c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average
increase was 0.26 mg/L with a range of -0.07 to 1.87
mg/L as total iron;
d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average
increase was 3.18 mg/L with a range of 1.29 to 4.21
mg/L as total iron; and
e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average
increase was 0.84 mg/L with a range of 0.60 to 1.01
mg/L as total iron.

D.2.7 Magnesium Concentration

D.2.7.1 Copper Experiments

Figures D.2.7.1.1 and D.2.7.1.2 show the weekly changes in magnesium concentration of the experimental waters, for the immersion of copper at different pH and hardness settings. The average decrease and range by which the magnesium concentration changed for each setting during a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as CaCO3, average
increase was 0.08 mg/L with a range of -0.02 to 0.23
mg/L as Mg^{2+};

Figures D.2.6.1.1 & D.2.6.1.2
Weekly Changes in Iron Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

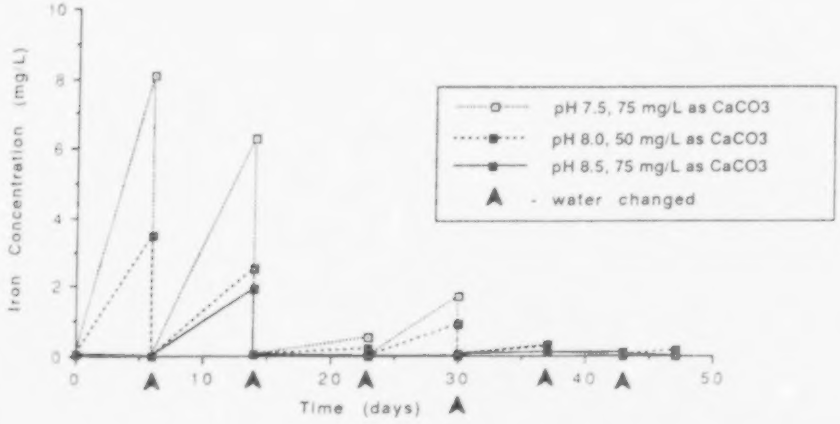
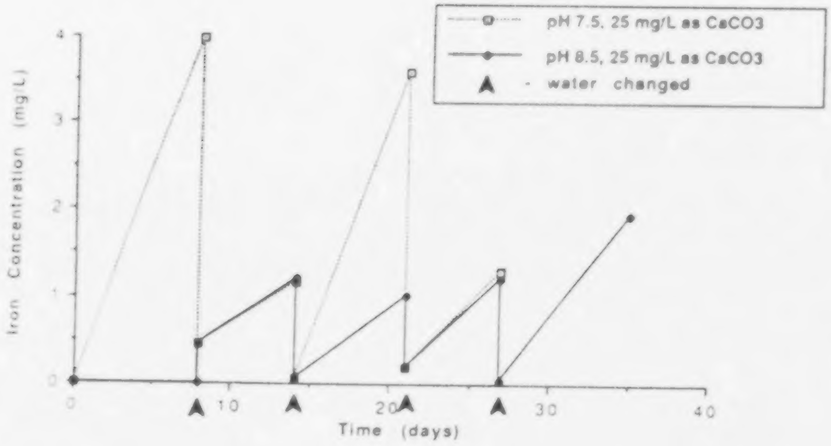


Figure D.2.6.1.2



b. pH 8.0 and hardness of 50 mg/L as CaCO3, average change was -0.03 mg/L with a range of -0.07 to 0.02 mg/L as Mg^{2+};

c. pH 8.5 and hardness of 75 mg/L as CaCO3, average change was -0.19 mg/L with a range of -0.26 to -0.10 mg/L as Mg^{2+};

d. pH 7.5 and hardness of 25 mg/L as CaCO3, average increase was 0.14 mg/L with a range of 0.09 to 0.22 mg/L as Mg^{2+}; and

e. pH 8.5 and hardness of 25 mg/L as CaCO3, average increase was 0.08 mg/L with a range of 0.02 to 0.17 mg/L as Mg^{2+}.

The changes in magnitude of the magnesium concentration are shown decreasing with increasing pH and hardness for a weekly liquid retention time. The increased carbonate ion concentration combined with the local increase in pH at the metal's surface caused by corrosion, would have precipitated magnesium.

D.2.7.2 Ductile Iron Experiments

Figures D.2.7.1.1 and D.2.7.1.2 show the weekly changes in magnesium concentration of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. Unlike the copper results, the magnesium concentrations decreased for all settings. The average decrease and range by which the magnesium concentration changed for each setting for a weekly liquid retention time was:

Figures D.2.7.1.1 & D.2.7.1.2
Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

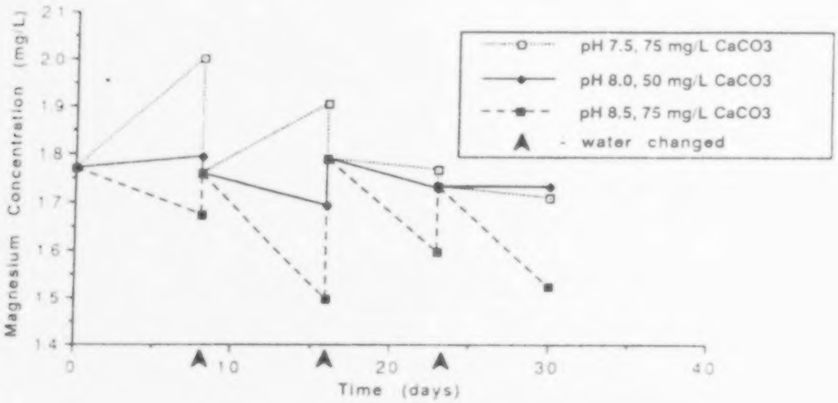
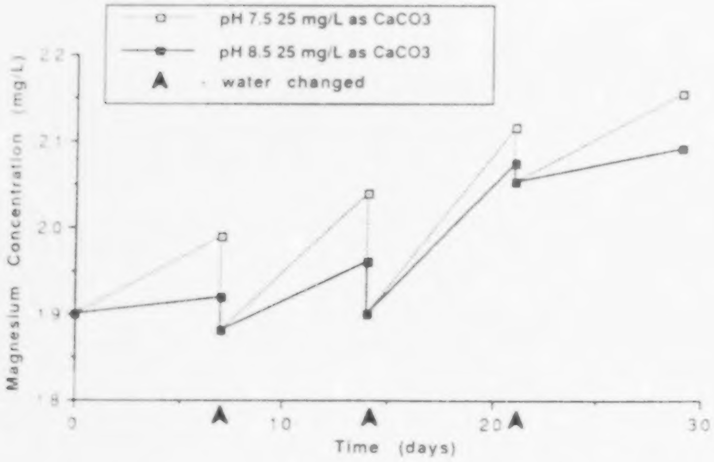


Figure D.2.7.1.2



a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average change was -0.18 mg/L with a range of -0.27 to -0.04 mg/L as Mg^{2+};

b. pH 8.0 and hardness of 50 mg/L as CaCO3, average change was -0.20 mg/L with a range of -0.38 to -0.16 mg/L as Mg^{2+};

c. pH 8.5 and hardness of 75 mg/L as CaCO3, average change was -0.36 mg/L with a range of -0.48 to -0.19 mg/L as Mg^{2+};

d. pH 7.5 and hardness of 25 mg/L as CaCO3, average change was -0.05 mg/L with a range of -0.19 to 0.02 mg/L as Mg^{2+}; and

e. pH 8.5 and hardness of 25 mg/L as CaCO3, average change was -0.14 mg/L with a range of -0.48 to 0.36 mg/L as Mg^{2+}.

The decreases are attributed to local increases in pH at the metal's surface, caused by corrosion and the increased alkalinity. The magnitude of the decreases are shown increasing with increasing pH and hardness.

D.2.8 pH

D.2.8.1 Copper Experiments

Figures D.2.8.1.1, D.2.8.1.2, D.2.8.1.3, D.2.8.1.4, and D.2.8.1.5 show the daily changes in pH of the experimental waters, for the immersion of copper at different pH and hardness settings. The pH varied the most immediately after changing the water. Only after several days, did the variation in pH

Figures D.2.7.2.1 & D.2.7.2.2
Weekly Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

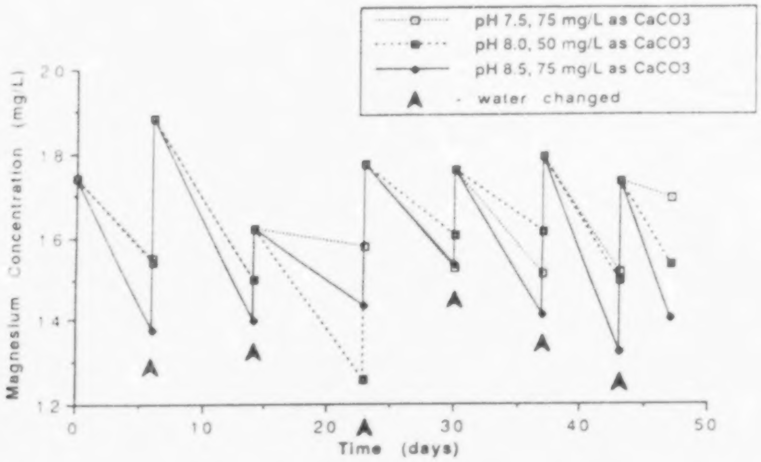


Figure D.2.7.2.2

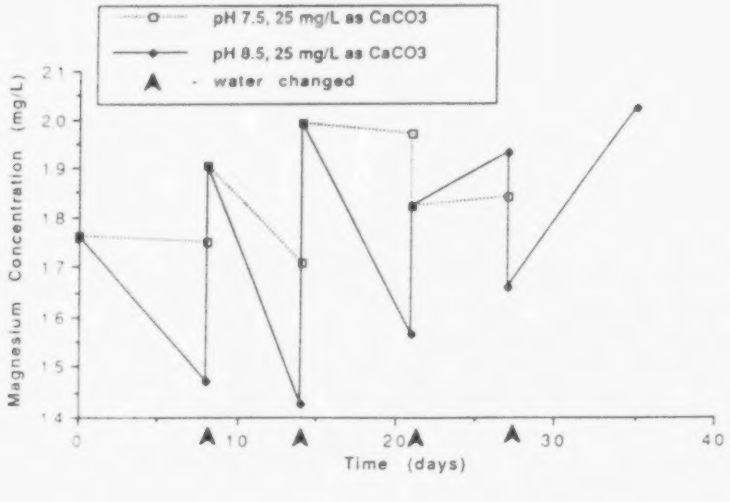


Figure D.2.8.1.1
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH 7.5 and Hardness 75 mg/L as CaCO3

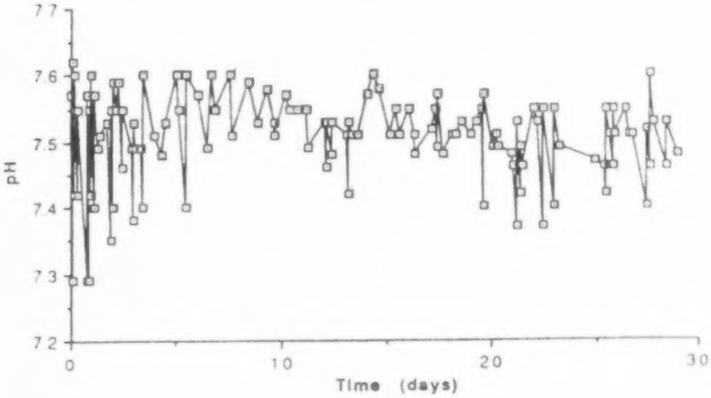


Figure D.2.8.1.2
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH 8.0 and Hardness 50 mg/L as CaCO3

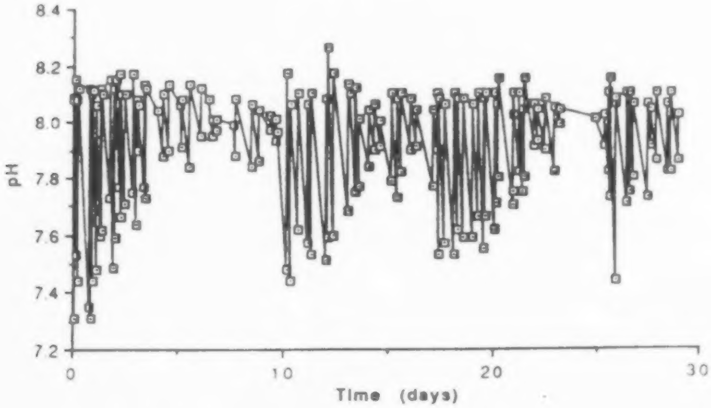


Figure D.2.8.1.3
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH 8.5 and Hardness 75 mg/L as CaCO3

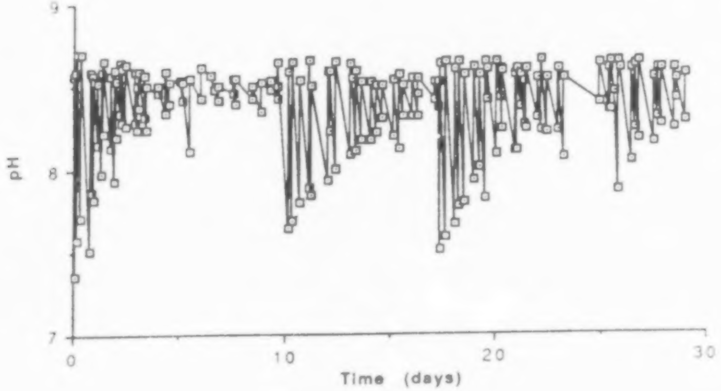


Figure D.2.8.1.4
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH 7.5 and Hardness 25 mg/L as CaCO3

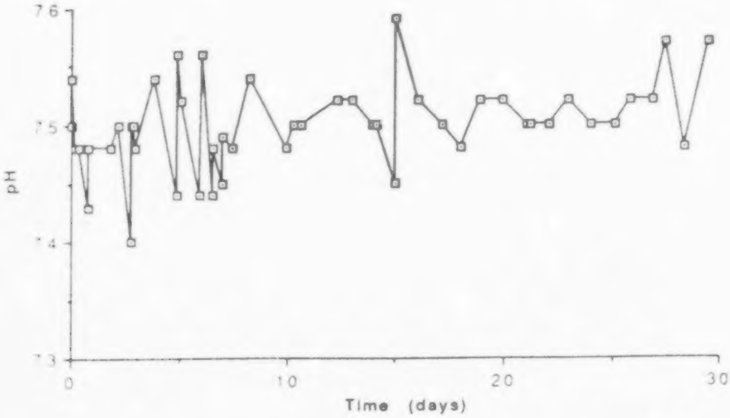
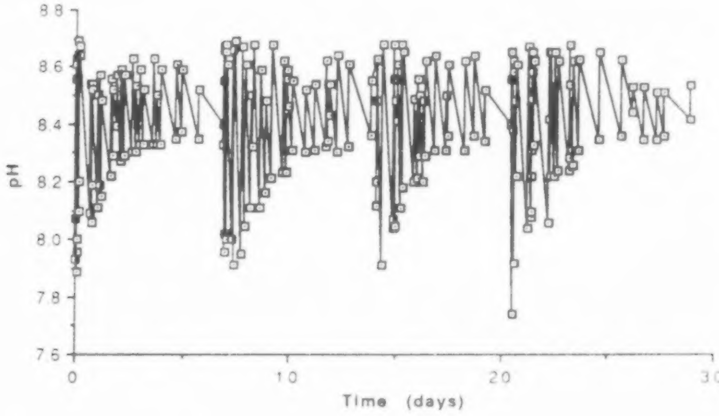


Figure D.2.8.1.5
Daily Changes in pH of the Experimental Water for the Immersion of Copper at pH 8.5 and Hardness 25 mg/L as $CaCO_3$



decrease due to the buffering capacity having increased from sodium hydroxide and lime additions for a weekly liquid retention time.

D.2.8.2 Ductile Iron Experiments

Figures D.2.8.2.1, D.2.8.2.2, D.2.8.2.3, D.2.8.2.4, and D.2.8.2.5 show the daily changes in pH of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. The pattern by which the pH varied for the different settings was similar to the copper results, with the only difference being in the magnitude. In comparison to copper, the initial magnitude by which pH varied, for immediately after changing the water was greater for the ductile iron experiments.

D.2.9. Total Hardness Concentration

D.2.9.1 Copper Experiments

Figures D.2.9.1.1, D.2.9.1.2, D.2.9.1.3, and D.2.9.1.4 show the daily changes in hardness concentration of the experimental waters, for the immersion of copper at different pH and hardness settings. The daily average decrease and range by which the total hardness concentration changed from the desired setting was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average change was -0.8 mg/L with a range of -7.4 to 3.9 mg/L as $CaCO_3$;

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average change was -2.4 mg/L with a range of -1.7 to 4.0 mg/L as $CaCO_3$;

Figure D.2.8.2.1
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH 7.5 and Hardness 75 mg/L as $CaCO_3$

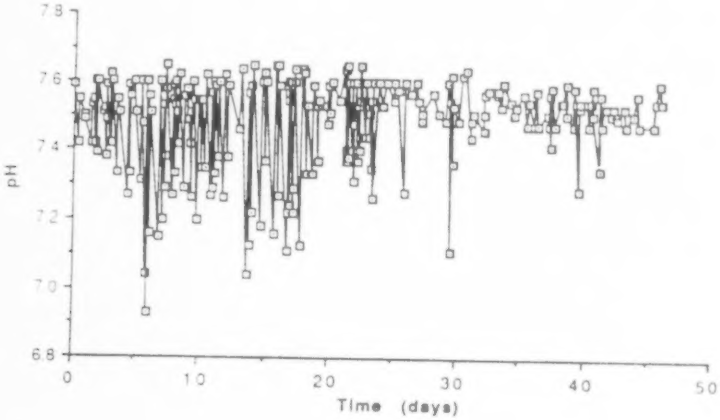


Figure D.2.8.2.2
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH 8.0 and Hardness 50 mg/L as $CaCO_3$

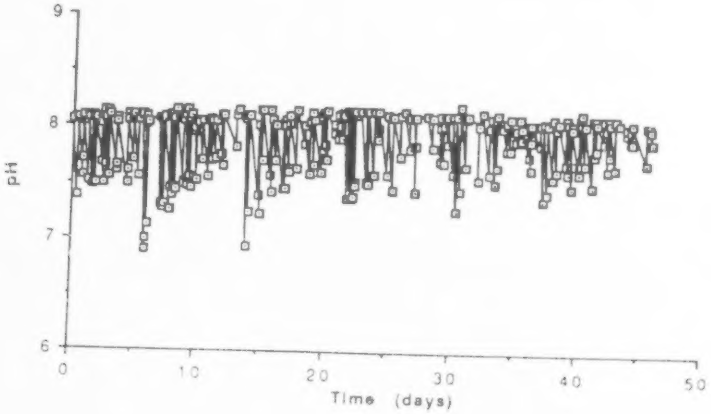


Figure D.2.8.2.3
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH 8.5 and Hardness 75 mg/L as $CaCO_3$

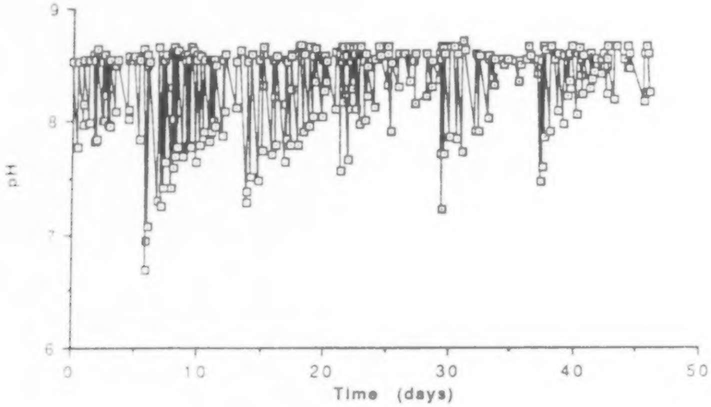


Figure D.2.8.2.4
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH 7.5 and Hardness 25 mg/L as $CaCO_3$

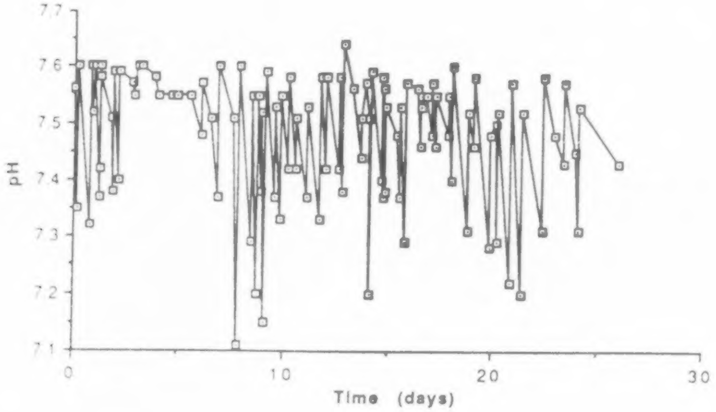
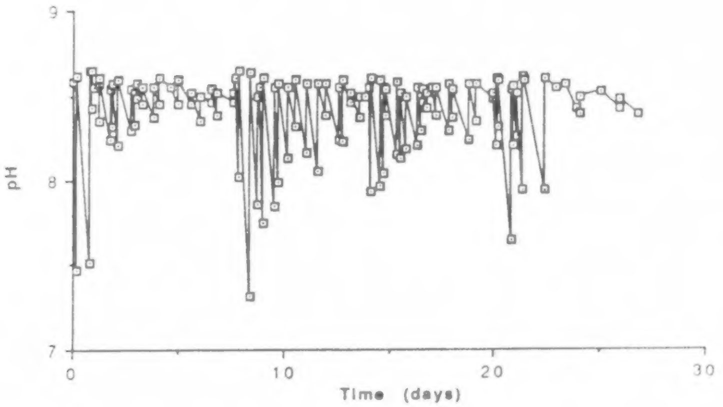


Figure D.2.8.2.5
Daily Changes in pH of the Experimental Water for the Immersion of Ductile Iron at pH 8.5 and Hardness 25 mg/L as $CaCO_3$



c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average change was -12.4 mg/L with a range of -14.8 to -7.7 mg/L as $CaCO_3$;

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 1.3 mg/L with a range of 0.0 to 1.8 mg/L as $CaCO_3$; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 1.6 mg/L with a range of 0.6 to 2.6 mg/L as $CaCO_3$.

The magnitude by which the hardness concentration decreased, increased with increasing pH and hardness. The largest decreases in hardness concentration occured for the setting: pH 8.5 with a total hardness concentration 75 mg/L as $CaCO_3$. This was attributed to the decrease in the magnesium concentration. However, regardless of setting, no coatings of $CaCO_3$ were visually observed to have formed on coupon surfaces. Stated previously, was that copper, when exposed alone, does not generate sufficient cell activity to have $CaCO_3$ deposit on its surface.

D.2.9.2 Ductile Iron Experiments

Figures D.2.9.2.1, D.2.9.2.2, D.2.9.2.3, D.2.9.2.4, and D.2.9.2.5 show the daily changes in the total hardness concentration of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. Unlike the copper results, the hardness concentrations generally decreased for the immersion of ductile iron on a daily basis. Coatings of $CaCO_3$ were observed to form on the surfaces of ductile iron with the exception of the settings pH 7.5 and 8.5 for hardness concentrations of 25 mg/L as $CaCO_3$. As

Figure D.2.9.1.1
Daily Changes in Total Hardness Concentration for the Immersion of Copper for the Setting: pH 7.5 and Hardness Concentration 75 mg/L as CaCO3

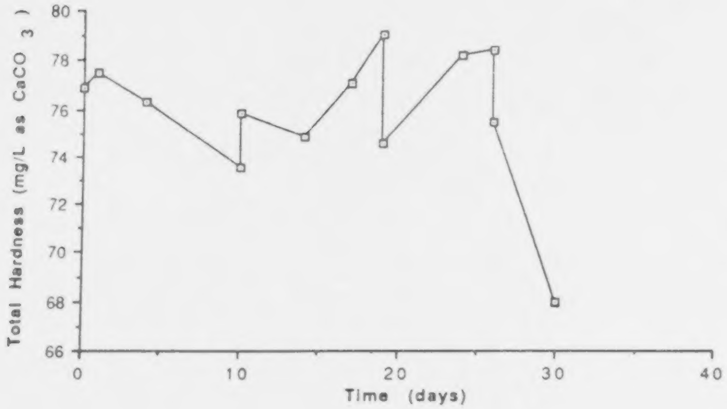


Figure D.2.9.1.2
Daily Changes in Total Hardness Concentration for the Immersion of Copper for the Setting: pH 8.0 and Hardness Concentration 50 mg/L as CaCO3

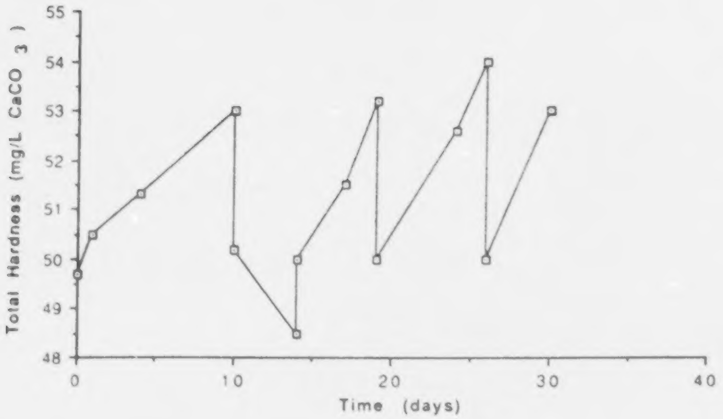


Figure D.2.9.1.3
Daily Changes in Total Hardness Concentration for the Immersion of Copper for the Setting: pH 8.5 and Hardness Concentration 75 mg/L as CaCO3

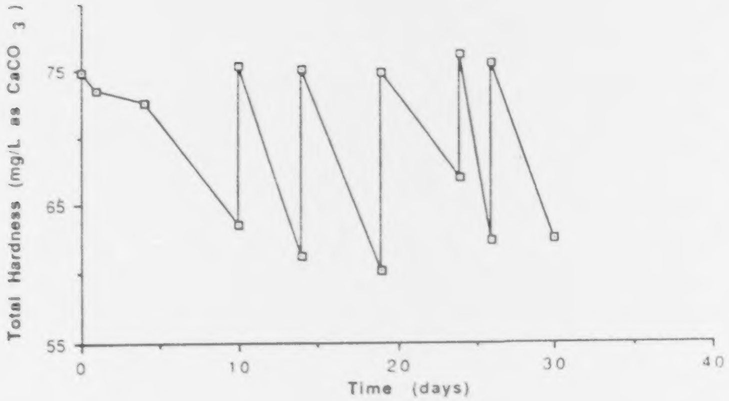
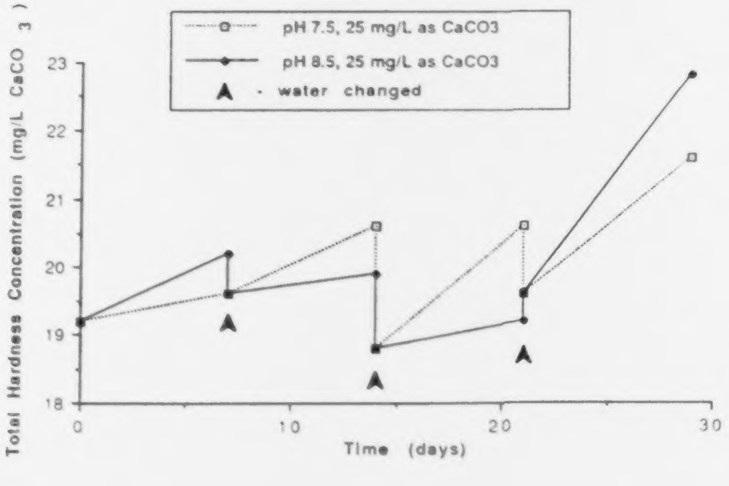


Figure D.2.9.1.4
Daily Changes in Total Hardness Concentration for the Immersion of Copper for the Setting: pH's 7.5, 8.5 and Hardness Concentration 25 mg/L as CaCO3



well, the tendency of the data shows that the higher the pH setting and hardness concentration, the greater the daily decrease in total hardness concentration. The average decrease and range by which the total hardness concentration changed from its desired setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average change was -13.0 mg/L with a range of -51.0 to -8.0 mg/L as $CaCO_3$;

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average change was -6.0 mg/L with a range of -28.8 to -0.7 mg/L as $CaCO_3$;

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average change was -26.0 mg/L with a range of -62.5 to -18.8 mg/L as $CaCO_3$;

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average change was -1.0 mg/L with a range of -7.0 to 3.8 mg/L as $CaCO_3$; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average change was -1.5 mg/L with a range of -4.7 to -0.2 mg/L as $CaCO_3$.

D.2.10 Silicate Concentration

D.2.10.1 Copper Experiments

Figures D.2.10.1.1 and D.2.10.1.2 show the weekly increases in silicate concentration of the experimental waters, for the immersion of copper at different pH and hardness settings. The average increase and range by which

Figure D.2.9.2.1
Daily Changes in Total Hardness Concentration for the Immersion of Ductile Iron for the Setting: pH 7.5 and Hardness Concentration 75 mg/L as $CaCO_3$

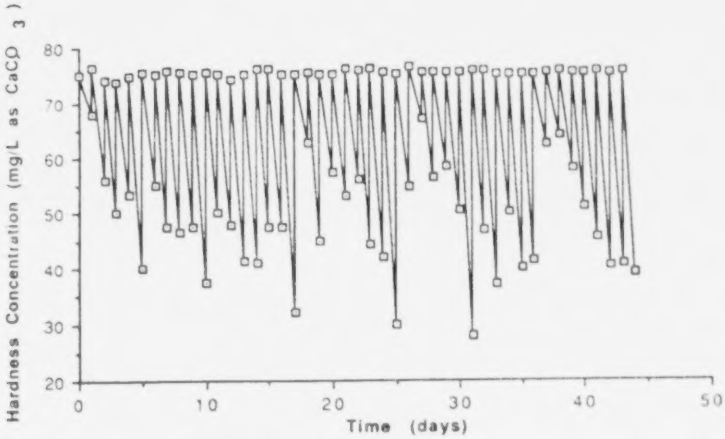


Figure D.2.9.2.2
Daily Changes in Total Hardness Concentration for the Immersion of Ductile Iron for the Setting: pH 8.0 and Hardness Concentration 50 mg/L as $CaCO_3$

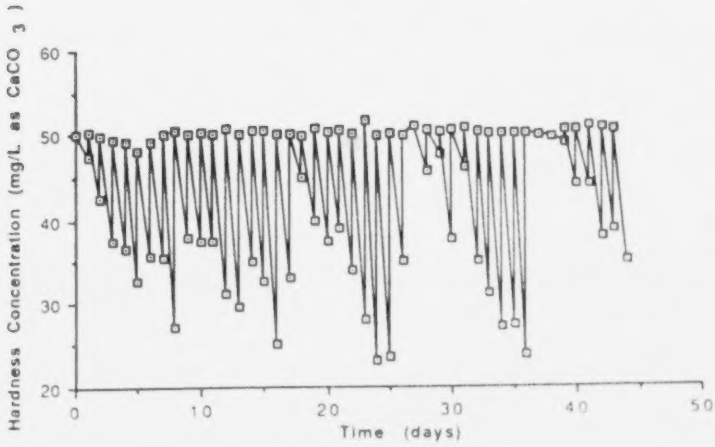


Figure D.2.9.2.3
Daily Changes in Total Hardness Concentration for the Immersion of Ductile Iron for the Setting: pH 8.5 and Hardness Concentration 75 mg/L as CaCO3

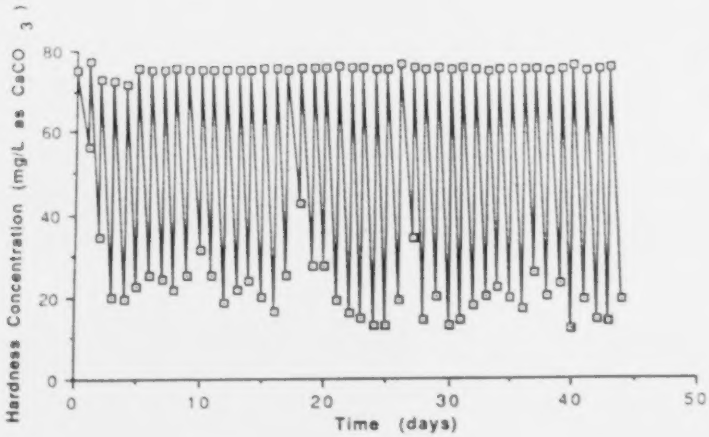


Figure D.2.9.2.4
Daily Changes in Total Hardness Concentration for the Immersion of Ductile Iron for the Setting: pH 7.5 and Hardness Concentration 25 mg/L as CaCO3

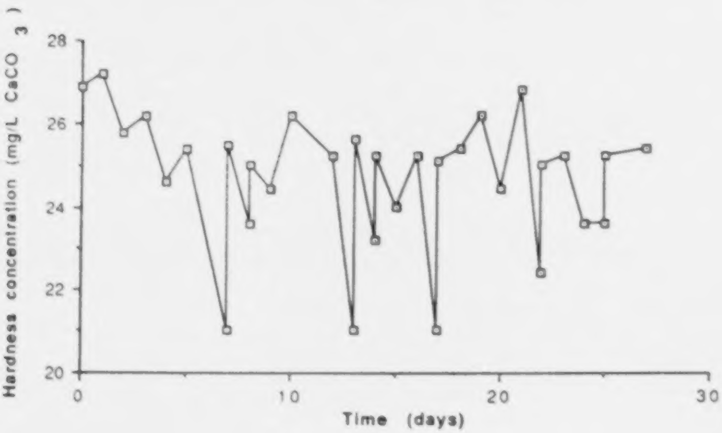
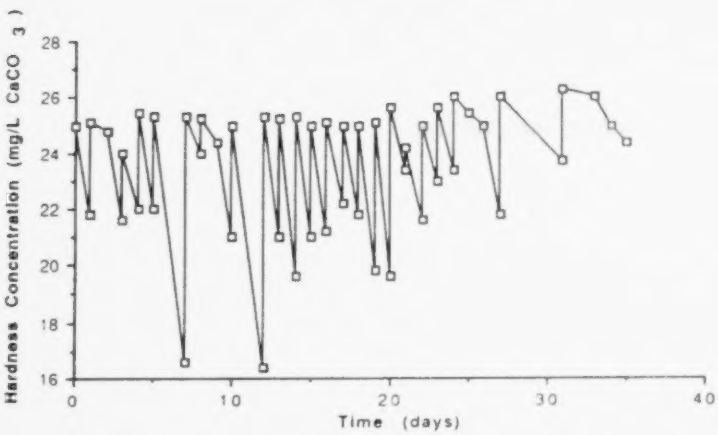


Figure D.2.9.2.5
Daily Changes in Total Hardness Concentration for the Immersion of Ductile Iron for the Setting: pH 8.5 and Hardness Concentration 25 mg/L as CaCO3



the silicate concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 0.11 mg/L with a range of -0.20 to 0.25 mg/L as Si;

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 0.01 mg/L with a range of -0.22 to 0.12 mg/L as Si

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 0.02 mg/L with a range of -0.02 to 0.15 mg/L as Si

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 0.06 mg/L with a range of -0.01 to 0.14 mg/L as Si; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 0.09 mg/L with a range of 0.02 to 0.18 mg/L as Si.

D.2.10.2 Ductile Iron Experiments

Figures D.2.10.2.1 and D.2.10.2.2 show the weekly increases in silicate concentration of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. The average increase and range by which the silicate concentration changed for each setting for a weekly liquid retention time was:

Figures D.2.10.1.1 & D.2.10.1.2

Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

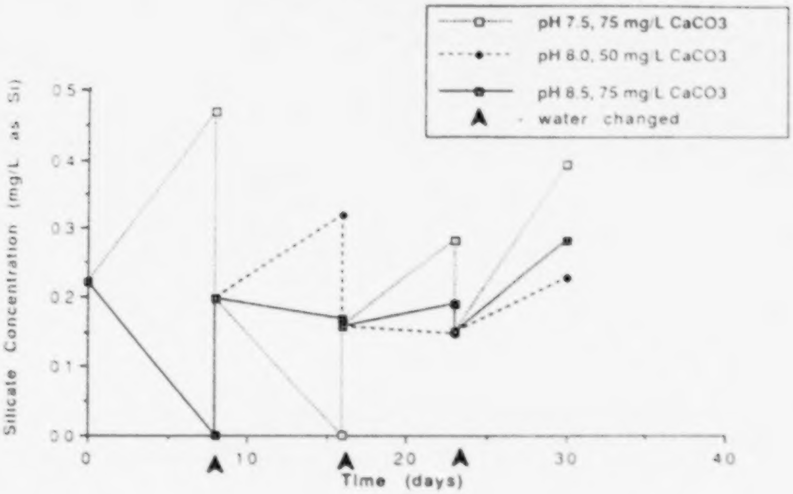
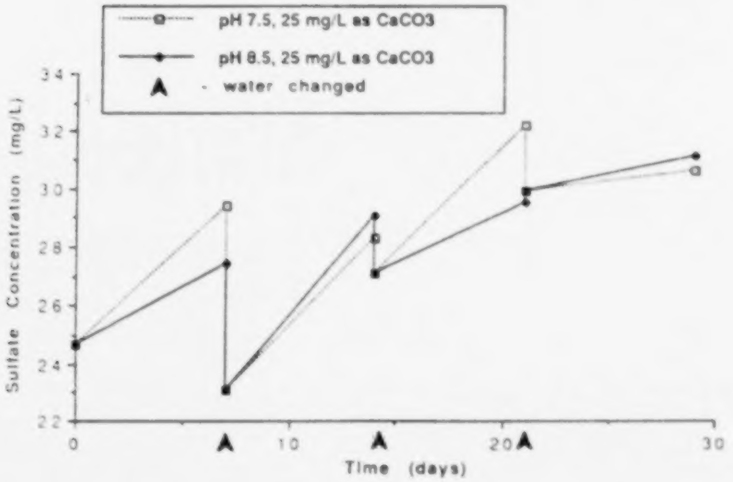


Figure D.2.10.1.2



Figures D.2.10.2.1 & D.2.10.2.2
Weekly Changes in Silicate Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

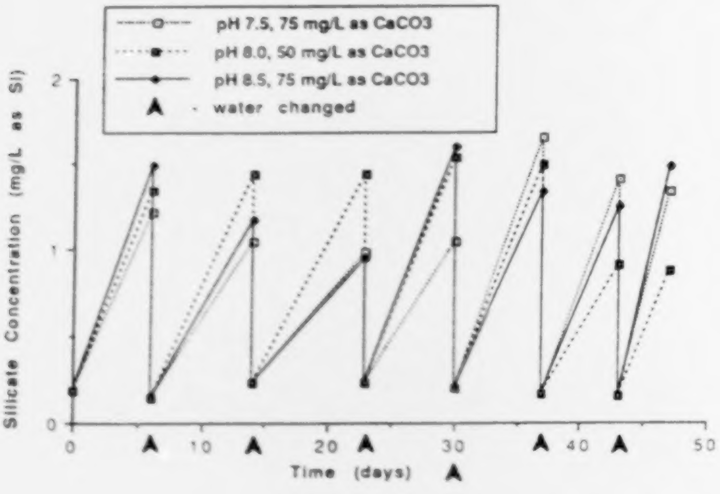
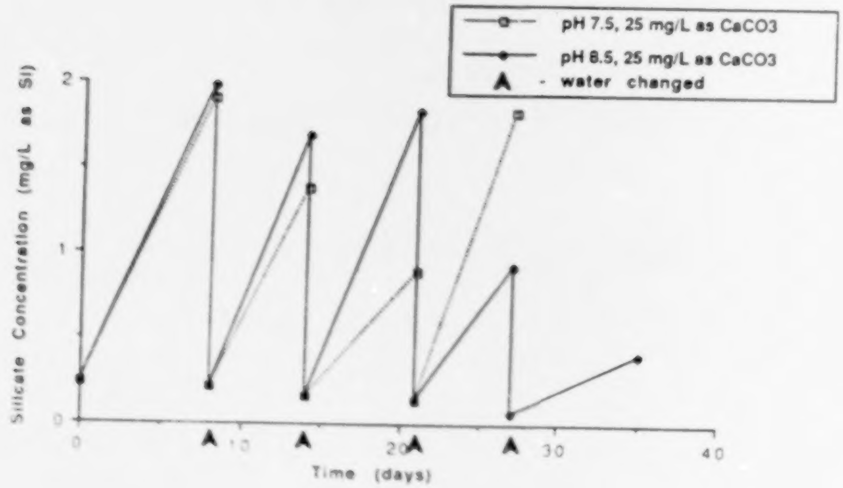


Figure D.2.10.2.2



a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average
increase was 1.06 mg/L with a range of 0.75 to 1.46
mg/L as Si;

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average
increase was 1.11 mg/L with a range of 0.72 to 1.32
mg/L as Si

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average
increase was 1.15 mg/L with a range of 0.73 to 1.38
mg/L as Si

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average
increase was 1.32 mg/L with a range of 1.02 to 1.65
mg/L as Si; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average
increase was 0.84 mg/L with a range of 0.60 to 1.01
mg/L as Si

D.2.11 Sodium Concentration

D.2.11.1 Copper Experiments

Figures D.2.11.1.1 and D.2.11.1.2 show the weekly increases in sodium concentration of the experimental waters, from primarily, sodium hydroxide addition. The average increase and range by which the sodium concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average
increase was 25.66 mg/L with a range of 15.04 to 37.14
mg/L as Na^+;

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 98.37 mg/L with a range of 92.43 to 104.55 mg/L as Na^+;

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 226.99 mg/L with a range of 187.63 to 250.11 mg/L as Na^+;

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 53.71 mg/L with a range of 45.48 to 66.15 mg/L as Na^+; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 149.87 mg/L with a range of 44.98 to 198.49 mg/L as Na^+.

D.2.11.2 Ductile Iron Experiments

Figures D.2.11.2.1 and D.2.11.2.2 show the weekly increases in the sodium concentration of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. The average increase and range by which the sodium concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 70.38 mg/L with a range of 40.79 to 96.97 mg/L as Na^+;

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 138.30 mg/L with a range of 75.48 to 266.40 mg/L as Na^+;

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 216.14 mg/L with a range of 158.35 to 275.69 mg/L as Na^+;

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 69.11 mg/L with a range of 58.29 to 81.92 mg/L as Na^+; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 224.40 mg/L with a range of 222.40 to 225.55 mg/L as Na^+.

D.2.12 Sulfate Concentration

D.2.12.1 Copper Experiments

Figures D.2.12.1.1 and D.2.12.1.2 show the weekly changes in sulfate concentration of the experimental waters, for the immersion of copper at different pH and hardness settings. The average decrease and range by which the sulfate concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average change was -0.33 mg/L with a range of -1.20 to 0.08 mg/L as SO_4^{2-};

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average change was -0.16 mg/L with a range of -0.71 to 0.28 mg/L as SO_4^{2-};

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average change was -0.46 mg/L with a range of -1.16 to 0.16 mg/L as SO_4^{2-};

Figures D.2.11.1.1 & D.2.11.1.2
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

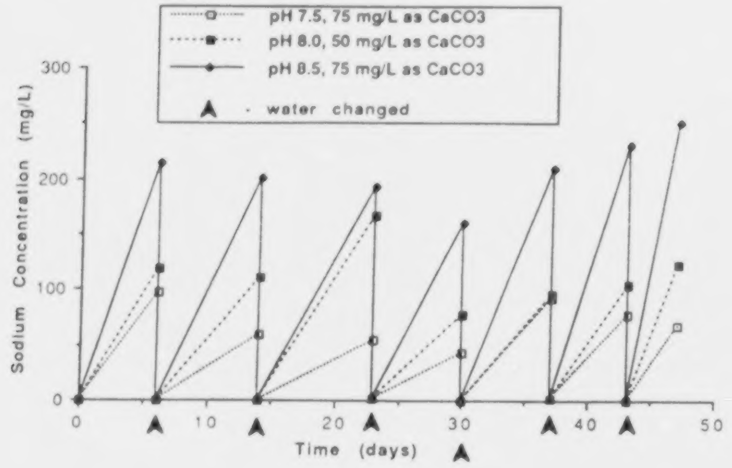
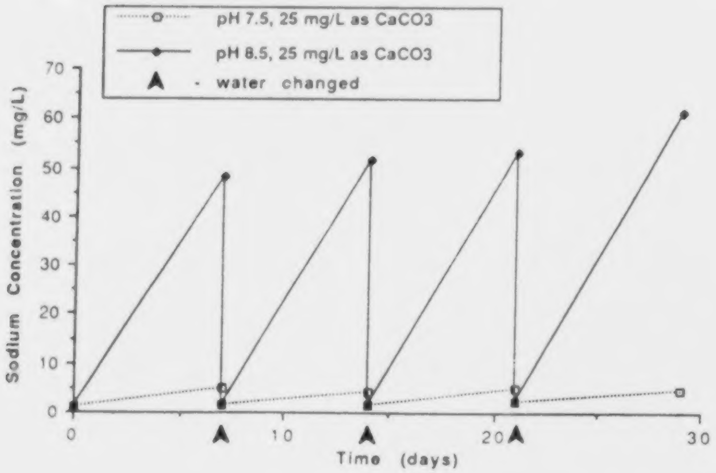


Figure D.2.11.1.2



Figures D.2.11.2.1 & D.2.11.2.2
Weekly Changes in Sodium Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

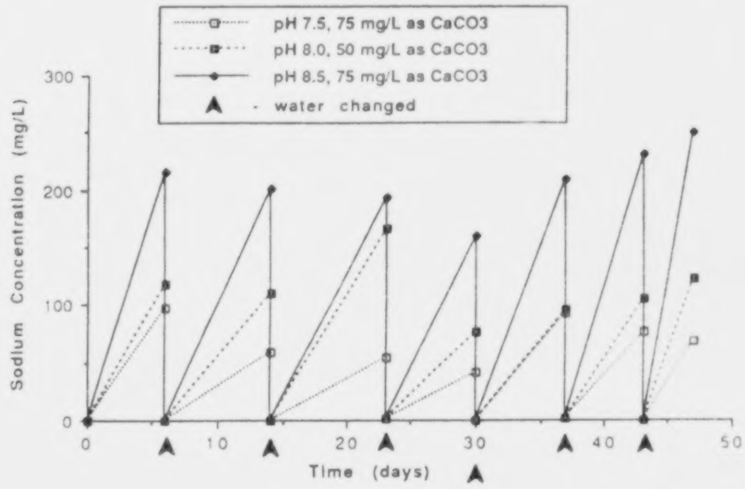
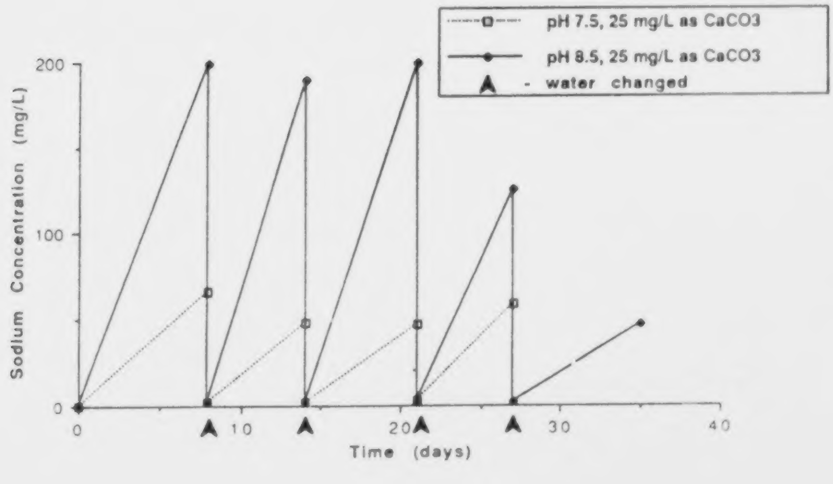


Figure D.2.11.2.2



d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 0.39 mg/L with a range of 0.07 to 0.52 mg/L as SO_4^{2-} and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 0.32 mg/L with a range of 0.12 to 0.60 mg/L as SO_4^{2-}.

D.2.12.2 Ductile Iron Experiments

Figures D.2.12.2.1 and D.2.12.2.2 show the weekly decreases in sulfate concentration of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. The average decrease and range by which the sulfate concentration changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average change was -1.40 mg/L with a range of -2.95 to -0.44 mg/L as SO_4^{2-};

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average change was -1.50 mg/L with a range of -3.08 to -0.23 mg/L as SO_4^{2-};

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average change was -1.40 mg/L with a range of -3.38 to -0.08 mg/L as SO_4^{2-};

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average change was -1.56 mg/L with a range of -2.15 to -1.23 mg/L as SO_4^{2-} and

Figures D.2.12.1.1 & D.2.12.1.2
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

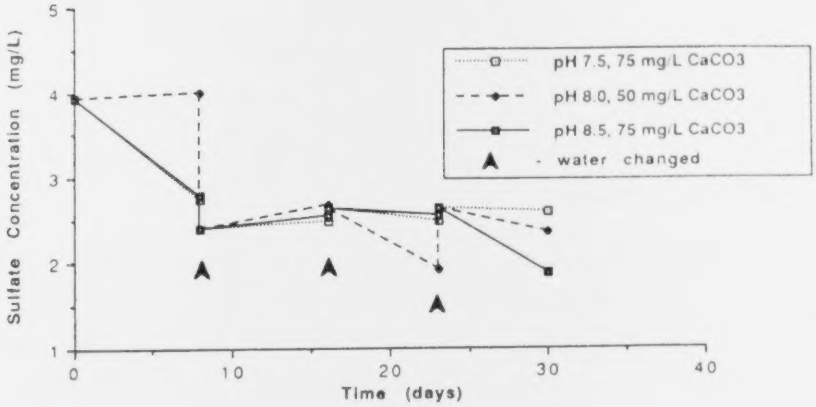
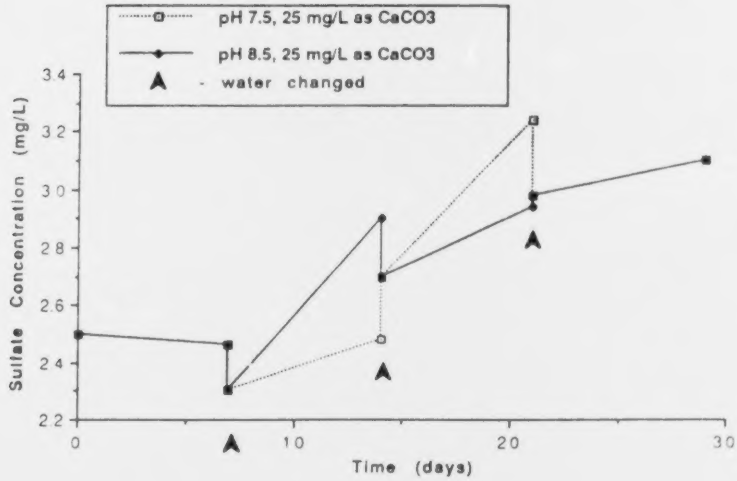


Figure D.2.12.1.2



Figures D.2.12.2.1 & D.2.12.2.2
Weekly Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

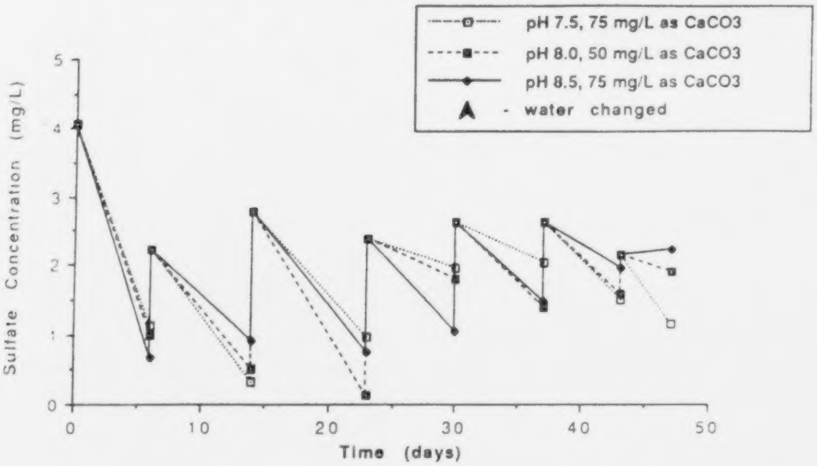
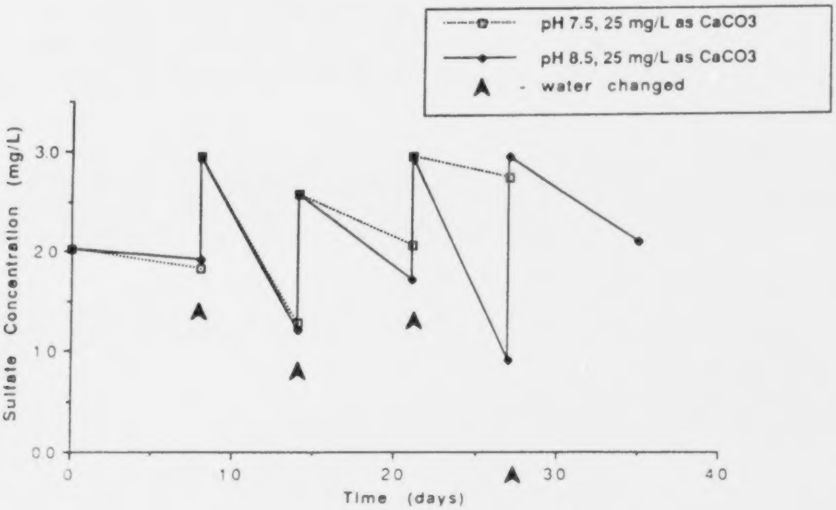


Figure D.2.12.2.2



e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average change was -1.75 mg/L with a range of -2.35 to -1.19 mg/L as SO_4^{2-}.

Sulfate can be reduced to sulfides by microorganisms, which in turn, can then be precipitated as a metal sulfide solid such as FeS. Analysis of the water used, as the experimental water, showed sulfate-reducing bacteria to be present. Sulfate-reducing bacteria are capable of living within the corrosion scale formed on the surfaces of ductile iron coupons. Their ability to use sulfate in a dissimilatory sulfur metabolism to assimilate organic matter, can decrease the water's sulfate concentration. Therefore, microbial activity can account for the decreases in sulfate concentration.

D.2.13 Temperature

The temperature at which the experiments were performed, ranged from 5 to 8.5 °C.

D.2.14 Turbidity

D.2.14.1 Copper Experiments

Figures D.2.14.1.1 and D.2.14.1.2 show the weekly changes in turbidity of the experimental waters, for the immersion of copper at different pH and hardness settings. The increases in turbidity are from the combination of copper corrosion, chemical addition and, to a lesser extent, from liquid losses due to evaporation. The average increase and range by which the turbidity changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 0.3 with a range of 0.0 to 0.7 NTU;

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 0.7L with a range of 0.1 to 1.8 NTU;

c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 0.3 with a range of -0.2 to 0.8 NTU;

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 0.7 with a range of 0.1 to 1.3 NTU; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 0.1 with a range of -0.5 to 0.6 NTU.

The increases in turbidity were generally lower with increasing pH and this is associated to lower corrosion rates with increasing pH.

D.2.14.2 Ductile Iron Experiments

Figures D.2.14.2.1 and D.2.14.2.2 show the weekly increases in turbidity of the experimental waters, for the immersion of ductile iron at different pH and hardness settings. The increases are associated to ductile iron corrosion and from the formation of $CaCO_3$. The greatest increases in turbidity occured during the initial two weeks of exposure, in which corrosion was highest. In addition, the magnitude of the turbidity increases are shown decreasing with increasing pH and hardness. This is from the removal of coupons and a reduction in corrosion with time. The average increase and range by which the turbidity changed for each setting for a weekly liquid retention time was:

a. pH 7.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 10.5 with a range of 1.1 to 30.9 NTU;

b. pH 8.0 and hardness of 50 mg/L as $CaCO_3$, average increase was 6.0 with a range of -0.3 to 18.9 NTU;

Figures D.2.14.1.1 & D.2.14.1.2

Weekly Changes in Turbidity of the Experimental Waters for the Immersion of Copper at Different pH and Hardness Settings

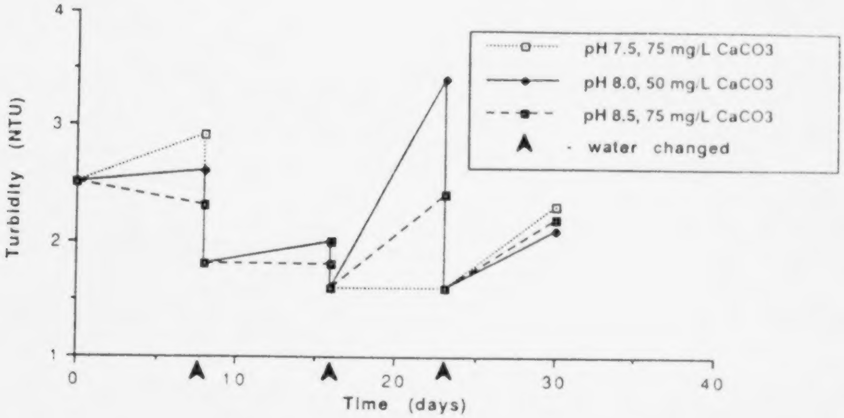
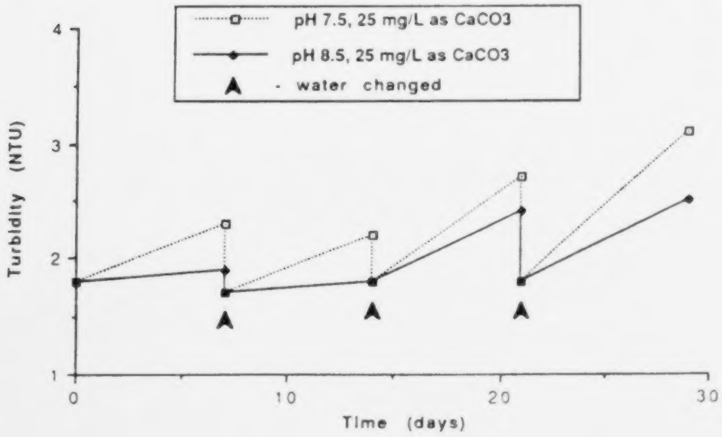


Figure D.2.14.1.2



Figures D.2.14.2.1 & D.2.14.2.2
Weekly Changes in Turbidity of the Experimental Waters for the Immersion of Ductile Iron at Different pH and Hardness Settings

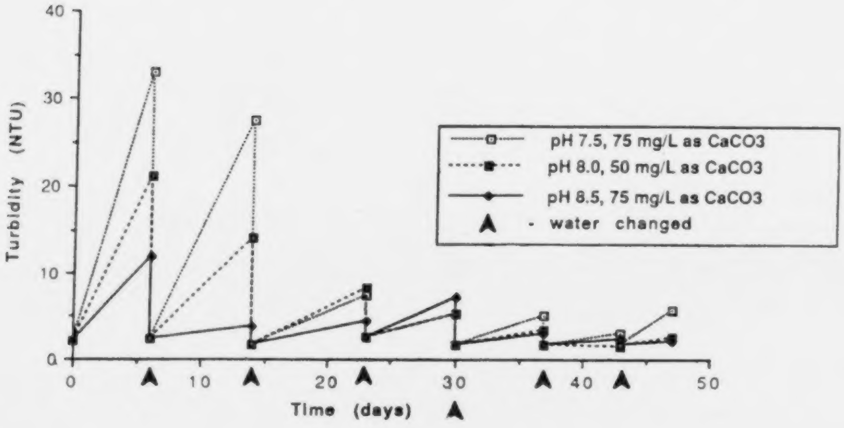
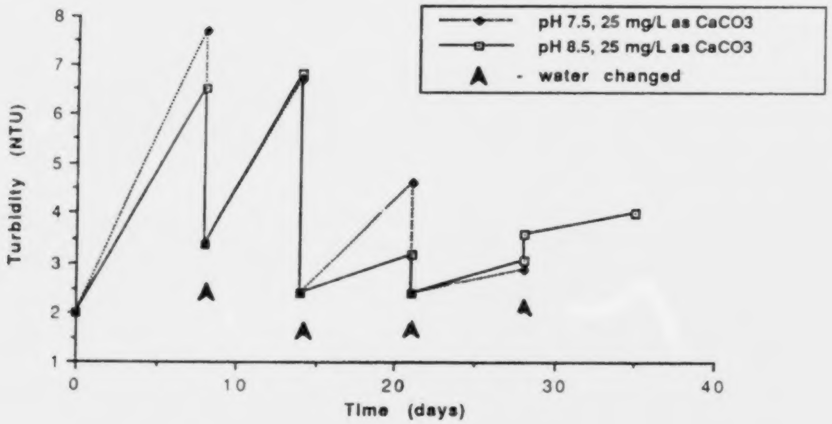


Figure D.2.14.2.2



c. pH 8.5 and hardness of 75 mg/L as $CaCO_3$, average increase was 3.1 with a range of 0.6 to 9.9 NTU;

d. pH 7.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 2.9 with a range of 0.5 to 5.7 NTU; and

e. pH 8.5 and hardness of 25 mg/L as $CaCO_3$, average increase was 2.0 with a range of 0.4 to 4.5 NTU.

Appendix E

Detailed Summary of the Water Quality Changes for the Sodium Silicate Tests.

The following is a detailed summary of the water quality changes for each setting of the sodium silicate experiments. Detailed are the changes in water quality throughout the duration of each corrosion test conducted using the inhibitor, sodium silicate.

E.1 Experimental Schedules

E.1.1 Copper Experiments

Figure E.1.1.1 is the experimental schedule for the removal of copper coupons, exposed to different silicate concentrations. Sample sets consisted of three coupons, which were removed weekly. The duration of the tests was approximately 19 days.

E.1.2 Ductile Iron Experiments

Figure E.1.2.1 is the experimental schedule for the removal of ductile iron coupons, exposed to different silicate concentrations. Sample sets consisted of two coupons, which were removed weekly. The duration of the tests was approximately 22 days.

E.2 Laboratory Water Characteristics

Throughout the experiments, several water quality parameters were monitored on a weekly basis. These parameters were measured prior to the immersion of coupons, and again when changing the water on a weekly basis. Presented, are the weekly variations in water quality, for the immersion of ductile iron and copper coupons at different silicate concentrations.

Figure E.1.1.1
Experimental Schedule: 2.1, 4.0 and 5.9 mg/L as SiO_2

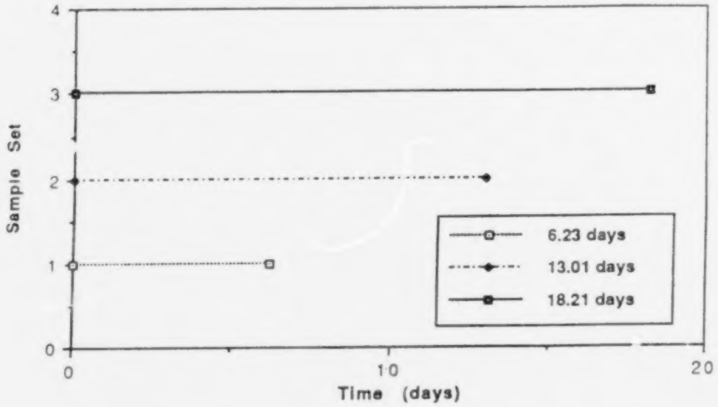
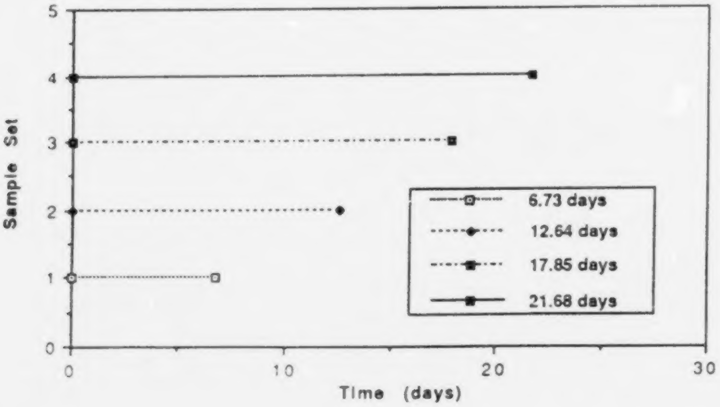


Figure E.1.2.1
Experimental Schedule: 6.9, 10.0, 13.4 and 21.0 mg/L as SiO_2



E.2.1 Alkalinity

E.2.1.1 Copper Experiments

Figure E.2.1.1.1 shows the weekly changes in alkalinity of the experimental waters, for the immersion of copper at different silicate concentrations. The average increase and range by which the alkalinity changed for each setting was:

a. 2.1 mg/L as SiO_2: average increase was 2.9 mg/L with a range of 1.4 to 5.6 mg/L as $CaCO_3$;
b. 4.0 mg/L as SiO_2: average increase was 4.7 mg/L with a range of 2.4 to 7.7 mg/L as $CaCO_3$; and
c. 5.9 mg/L as SiO_2: average increase was 6.4 mg/L with a range of 3.9 to 10.4 mg/L as $CaCO_3$.

The increases in alkalinity are primarily from sodium silicate addition.

E.2.1.2 Ductile Iron Experiments

Figure E.2.1.2.1 shows the changes in alkalinity of the experimental waters, for the immersion of ductile iron at different silicate concentrations. The average increase and range by which the alkalinity changed for each setting for an average liquid retention time of 3 days was:

a. 6.9 mg/L as SiO_2: average increase was 59.0 mg/L with a range of 41.8 to 80.3 mg/L as $CaCO_3$;
b. 10.0 mg/L as SiO_2: average increase was 52.5 mg/L with a range of 43.4 to 63.4 mg/L as $CaCO_3$;

Figure E.2.1.1.1
Weekly Changes in Alkalinity of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

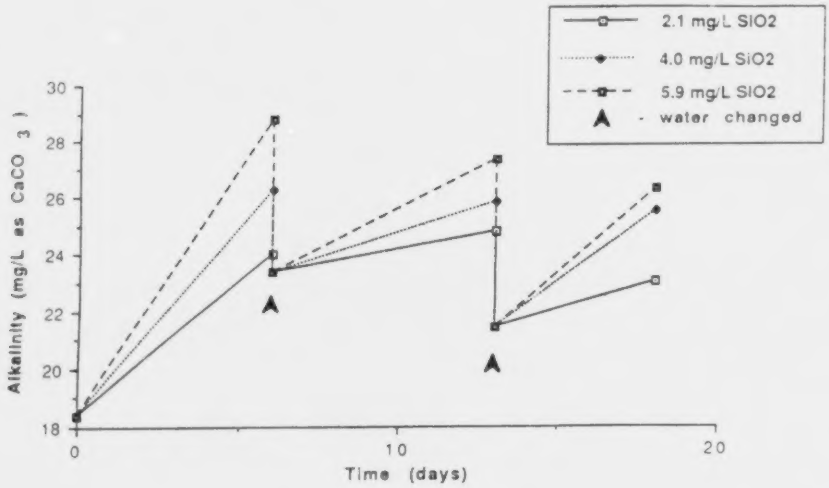
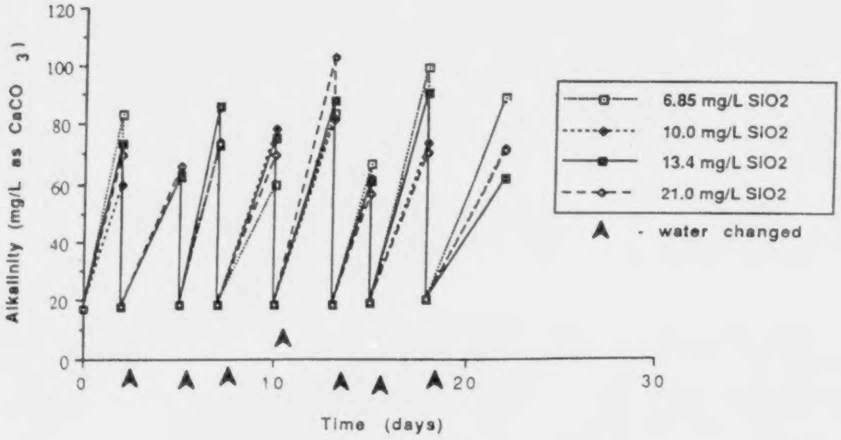


Figure E.2.1.2.1
Changes in Alkalinity of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations



c. 13.4 mg/L as SiO_2: average increase was 56.7 mg/L with a range of 42.1 to 71.9 mg/L as $CaCO_3$; and

d. 21.0 mg/L as SiO_2: average increase was 54.4 mg/L with a range of 38.6 to 84.6 mg/L as $CaCO_3$.

The increases in alkalinity are primarily from sodium hydroxide addition, and to a lesser extent, sodium silicate addition. Sodium hydroxide addition was to maintain the pH between the range of 7.0 to 7.5.

E.2.2 Calcium Concentration

E.2.2.1 Copper Experiments

Figure E.2.2.1.1 shows the weekly changes in calcium concentration of the experimental waters, for the immersion of copper at different silicate concentrations. The average increase and range by which the calcium concentration changed for each setting for a weekly liquid retention time was:

a. 2.1 mg/L SiO_2 concentration: average increase was 0.5 mg/L with a range of 0.5 to 0.6 mg/L as Ca^{2+};

b. 4.0 mg/L SiO_2 concentration: average increase was 0.5 mg/L with a range of 0.4 to 0.6 mg/L as Ca^{2+}; and

c. 5.9 mg/L SiO_2 concentration: average increase was 0.5 mg/L with a range of 0.3 to 0.8 mg/L as Ca^{2+}.

Slight increases in calcium concentration are from liquid losses due to evaporation for a weekly liquid retention time.

E.2.2.2 Ductile Iron Experiments

Figure E.2.2.2.1 shows the changes in calcium concentration of the experimental waters, for the immersion of ductile iron at different silicate concentrations. The average change by which the calcium concentration changed for each setting for an average liquid retention time of 3 days was:

a. 6.9 mg/L as SiO_2: average change was -0.1 mg/L with a range of -0.7 to 0.4 mg/L as Ca^{2+};
b. 10.0 mg/L as SiO_2: average increase was 0.1 mg/L with a range of -0.5 to 0.8 mg/L as Ca^{2+};
c. 13.4 mg/L as SiO_2: average change was -0.3 mg/L with a range of -1.4 to 0.6 mg/L as Ca^{2+}; and
d. 21.0 mg/L as SiO_2: average change was -0.2 mg/L with a range of -1.1 to 0.6 mg/L as Ca^{2+}.

E.2.3 Copper Concentration

E.2.3.1 Copper Experiments

Figure E.2.3.1.1 shows the weekly changes in copper concentration of the experimental waters, for the immersion of copper at different silicate concentrations. The average increase and range by which the copper concentration changed for each setting during a weekly retention time was:

a. 2.1 mg/L SiO_2 concentration: average increase was 1.14 mg/L with a range of 0.74 to 1.36 mg/L as Cu^{2+};
b. 4.0 mg/L SiO_2 concentration: average increase was 1.32 mg/L with a range of 0.84 to 1.64 mg/L as Cu^{2+}; and

Figure E.2.2.1.1
Weekly Changes in Calcium Concnetration of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

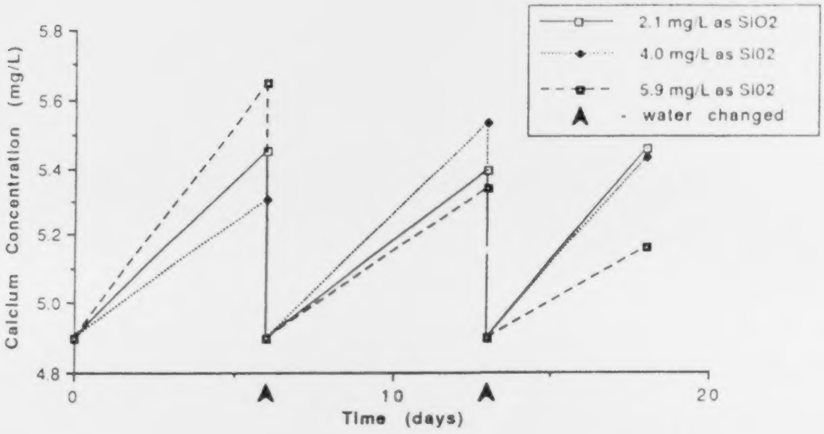


Figure E.2.2.2.1
Changes in Calcium Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations

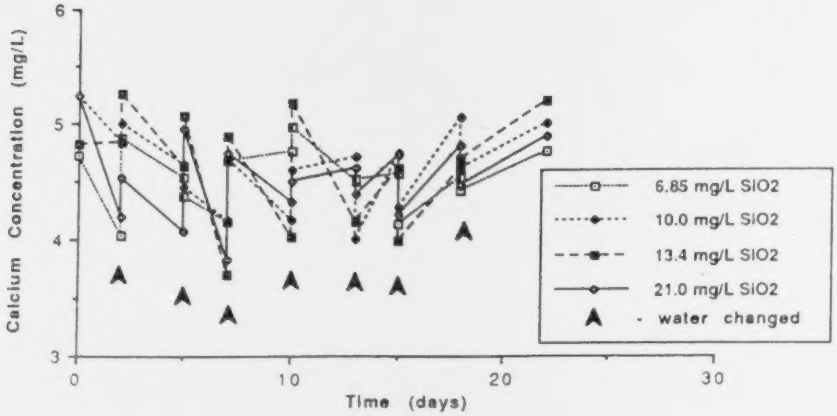
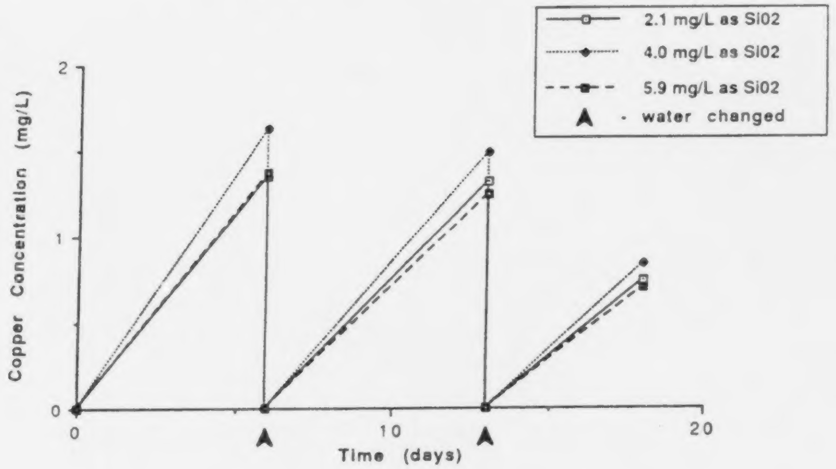


Figure E.2.3.1.1
Weekly Changes in Copper Concnetration of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations



c. 5.9 mg/L SiO_2 concentration: average increase was 1.11 mg/L with a range of 0.70 to 1.37 mg/L as Cu^{2+}.

The increases in copper concentration are from copper corrosion.

E.2.4 Chloride Concentration

E.2.4.1 Copper Experiments

Figure E.2.4.1.1 shows the weekly changes in chloride concentration, for the immersion of copper at different silicate concentrations. The average increase and range by which the chloride concentration changed for each setting during a weekly retention time was:

a. 2.1 mg/L SiO_2 concentration: average increase was 2.13 mg/L with a range of 1.91 to 2.53 mg/L as Cl^-;
b. 4.0 mg/L SiO_2 concentration: average increase was 2.16 mg/L with a range of 1.99 to 2.25 mg/L as Cl^-; and
c. 5.9 mg/L SiO_2 concentration: average increase was 2.39 mg/L with a range of 1.77 to 3.55 mg/L as Cl^-.

E.2.4.2 Ductile Iron Experiments

Figure E.2.4.2.1 shows the changes in chloride concentration, for the immersion of ductile iron at different silicate concentrations. The average increase and range by which the chloride concentration changed for each setting for an average liquid retention time of 3 days was:

a. 6.9 mg/L SiO_2 concentration: average increase was 2.26 mg/L with a range of -0.65 to 5.14 mg/L as Cl^-;

Figure E.2.4.1.1
Weekly Changes in Chloride Concnetration of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

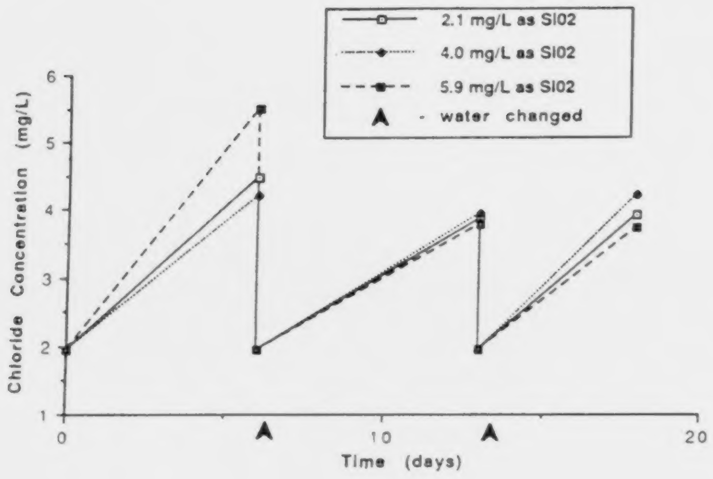
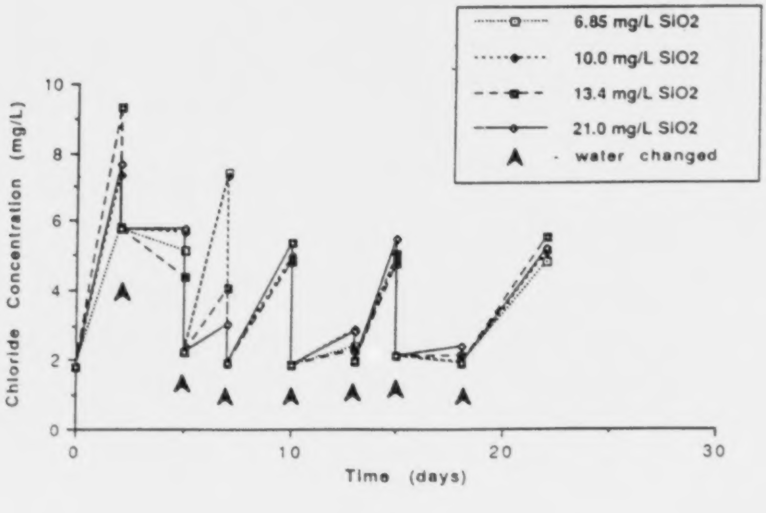


Figure E.2.4.2.1
Changes in Chloride Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations



b. 10.0 mg/L SiO_2 concentration: average increase was 2.56 mg/L with a range of -0.11 to 5.49 mg/L as Cl^-;

c. 13.4 mg/L SiO_2 concentration: average increase was 2.19 mg/L with a range of -1.40 to 7.50 mg/L as Cl^-; and

d. 21.0 mg/L SiO_2 concentration: average increase was 2.24 mg/L with a range of -0.04 to 5.83 mg/L as Cl^-.

E.2.5 Dissolved Oxygen Concentration

E.2.5.1 Copper Experiments

Figure E.2.5.1.1 shows the weekly variations in dissolved oxygen concentration, as measured when changing the experimental waters, for the immersion of copper at different silicate concentrations. The dissolved oxygen concentrations of the experimental waters were kept relatively constant by continual aeration of the waters. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. 2.1 mg/L SiO_2 concentration: average was 11.68 mg/L with a range of 11.65 to 11.70 mg/L as O_2;

b. 4.0 mg/L SiO_2 concentration: average was 11.67 mg/L with a range of 11.65 to 11.70 mg/L as O_2; and

c. 5.9 mg/L SiO_2 concentration: average was 11.66 mg/L with a range of 11.62 to 11.70 mg/L as O_2.

E.2.5.2 Ductile Iron Experiments

Figure E.2.5.2.1 shows the dissolved oxygen concentrations, as measured when changing the experimental waters, for the immersion of ductile iron at different silicate concentrations. The dissolved oxygen concentrations of the experimental waters were kept relatively constant by continual aeration of the waters. The average and range by which the dissolved oxygen concentration varied for each setting was:

a. 6.9 mg/L SiO_2 concentration: average was 11.25 mg/L
with a range of 11.20 to 11.33 mg/L as O_2;
b. 10.0 mg/L SiO_2 concentration: average was 11.26 mg/L
with a range of 11.15 to 11.36 mg/L as O_2;
c. 13.4 mg/L SiO_2 concentration: average was 11.26 mg/L
with a range of 11.18 to 11.37 mg/L as O_2;
d. 21.0 mg/L SiO_2 concentration: average was 11.28 mg/L
with a range of 11.25 to 11.35 mg/L as O_2;

E.2.6 Electrical Conductivity

E.2.6.1 Copper Experiments

Figure E.2.6.1.1 shows the weekly changes in electrical conductivity, for the immersion of copper at different silicate concentrations. The average increase and range by which the electrical conductivity changed for each setting during a weekly retention time was:

a. 2.1 mg/L SiO_2 concentration: average increase was 22.0
with a range of 17.0 to 28.0 umhos/cm;
b. 4.0 mg/L SiO_2 concentration: average increase was 24.0
with a range of 23.0 to 26.0 umhos/cm; and
c. 5.9 mg/L SiO_2 concentration: average increase was 24.0
with a range of 20.0 to 29.0 umhos/cm.

Figure E.2.5.1.1
Weekly Changes in Dissolved Oxygen Concnetration of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

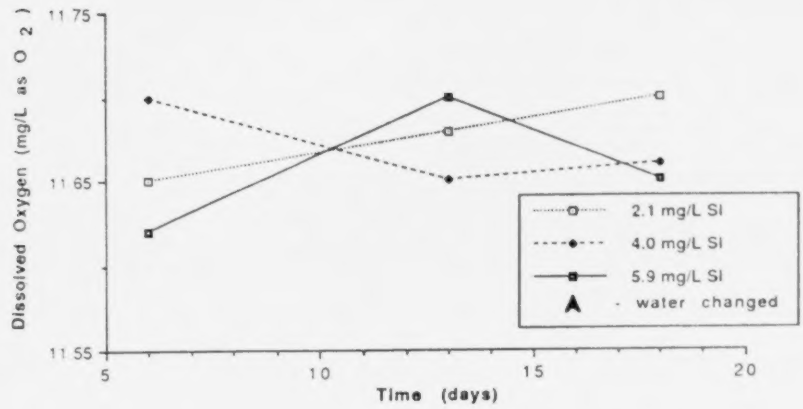
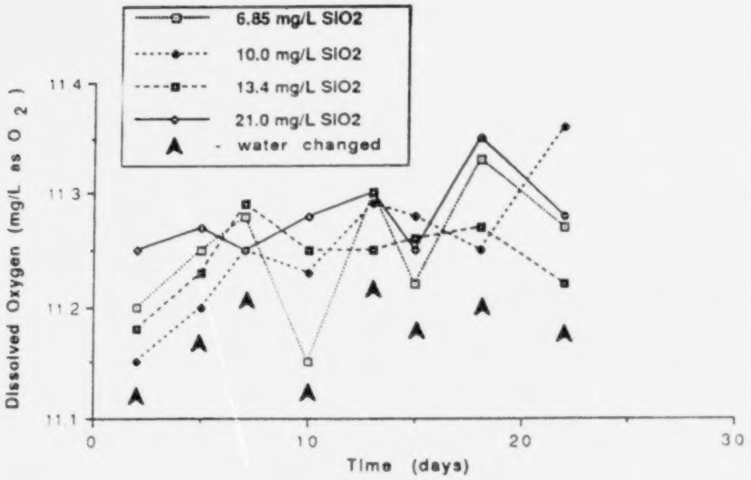


Figure E.2.5.2.1
Changes in Dissolved Oxygen Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations



Increases in electrical conductivity are primarily a contribution of sodium silicate addition and copper corrosion.

E.2.6.2 Ductile Iron Experiments

Figure E.2.6.2.1 shows the changes in electrical conductivity of the experimental waters, for the immersion of ductile iron at different silicate concentrations. The average increase and range by which the electrical conductivity changed for each setting for an average liquid retention time of 3 days was:

a. 6.9 mg/L as SiO_2: average increase was 71.7 with a range of 40.0 to 95.0 umhos/cm;
b. 10.0 mg/L as SiO_2: average increase was 69.3 with a range of 61.0 to 86.0 umhos/cm;
c. 13.4 mg/L as SiO_2: average increase was 77.0 with a range of 52.0 to 91.0 umhos/cm; and
d. 21.0 mg/L as SiO_2: average increase was 73.4 with a range of 61.0 to 111.0 umhos/cm.

Increases in electrical conductivity are attributed to the addition of sodium hydroxide and sodium silicate, and from ductile iron corrosion.

E.2.7 Magnesium Concentration

E.2.7.1 Copper Experiments

Figure E.2.7.1.1 shows the weekly changes in magnesium concentration of the experimental waters, for the immersion of copper at different silicate

Figure E.2.6.1.1
Weekly Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

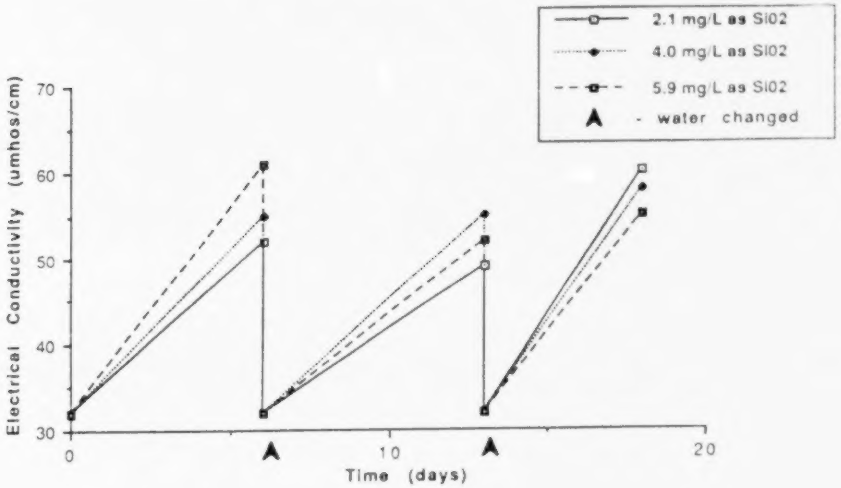
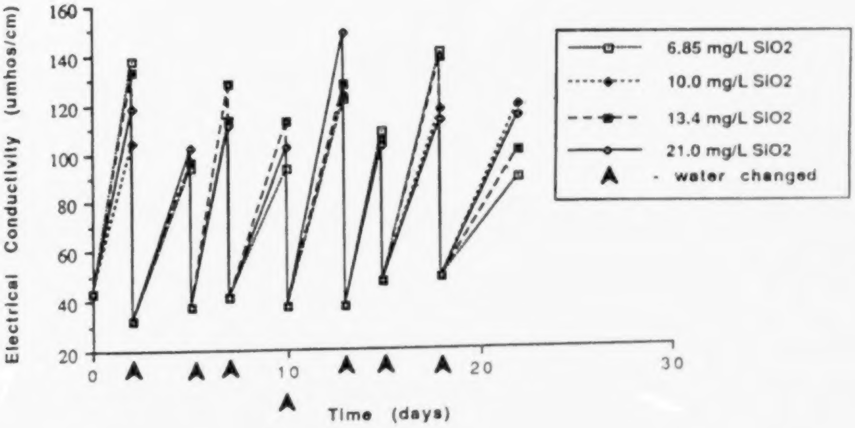


Figure E.2.6.2.1
Changes in Electrical Conductivity of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations



concentrations. The average increase and range by which the magnesium concentration changed for each setting for a weekly retention time was:

a. 2.1 mg/L SiO_2 concentration: average increase was 0.13 mg/L with a range of 0.10 to 0.15 mg/L as Mg^{2+};
b. 4.0 mg/L SiO_2 concentration: average increase was 0.13 mg/L with a range of 0.09 to 0.17 mg/L as Mg^{2+}; and
c. 5.9 mg/L SiO_2 concentration: average increase was 0.13 mg/L with a range of 0.07 to 0.20 mg/L as Mg^{2+}.

The magnesium concentrations increased slightly for a weekly liquid retention time. This is from liquid losses due to evaporation.

E.2.7.2 Ductile Iron Experiments

Figure E.2.7.2.1 shows the changes in magnesium concentration of the experimental waters, for the immersion of ductile iron at different silicate concentrations. The average change and range by which the magnesium concentration changed for each setting during an average 3 day liquid retention time was:

a. 6.9 mg/L as SiO_2: average change was -0.03 with a range of -0.18 to 0.07 mg/L as Mg^{2+};
b. 10.0 mg/L as SiO_2: average increase was 0.04 with a range of -0.17 to 0.10 mg/L as Mg^{2+};
c. 13.4 mg/L as SiO_2: average change was -0.03 with a range of -0.12 to 0.06 mg/L as Mg^{2+}; and
d. 21.0 mg/L as SiO_2: average change was -0.04 with a range of -0.11 to 0.11 mg/L as Mg^{2+}.

Figure E.2.7.1.1
Weekly Changes in Magnesium Concnetration of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

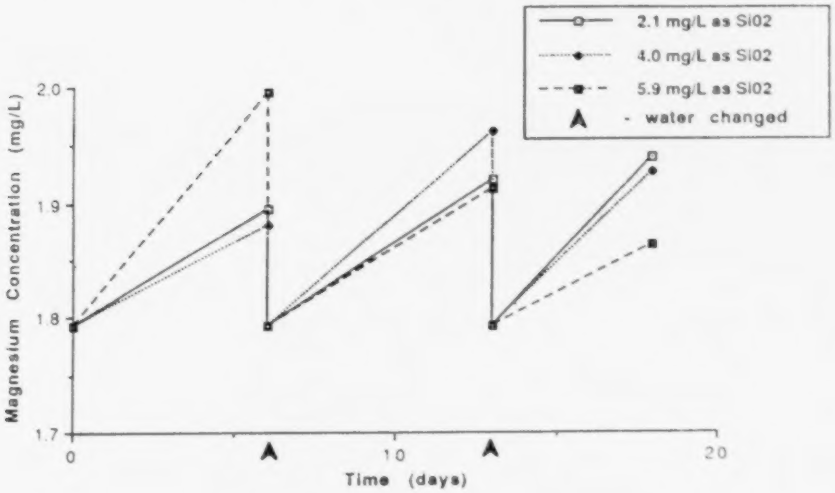
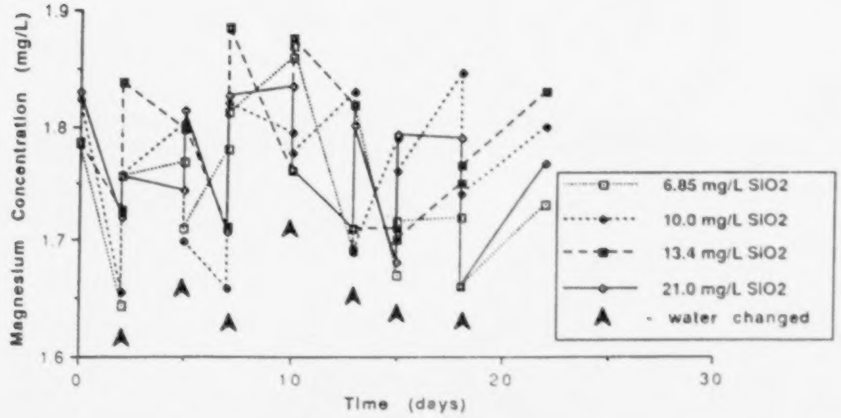


Figure E.2.7.2.1
Changes in Magnesium Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations



E.2.8 pH

E.2.8.1 Copper Experiments

Figure E.2.8.1.1 shows the daily changes in pH of the experimental waters, for the immersion of copper at different silicate concentrations.

E.2.8.2 Ductile Iron Experiments

Figures E.2.8.2.1, E.2.8.2.2, E.2.8.2.3, E.2.8.2.4, and E.2.8.2.5 show the daily changes in pH of the experimental waters, for the immersion of ductile iron at different silicate concentrations. For each setting, the pH varied from between 6.95 to 7.65 for the duration of the experiments.

E.2.9 Silicate Concentration

E.2.9.1 Copper Experiments

Figure E.2.9.1.1 shows the weekly increases in silicate concentration of the experimental waters, for the immersion of copper at different silicate concentrations. The average increase and range by which the silicate concentration changed for each setting was:

a. 2.1 mg/L as SiO_2: average increase was 0.12 mg/L with a range of 0.04 to 0.20 mg/L as Si;
b. 4.0 mg/L as SiO_2: average increase was 0.29 mg/L with a 0.03 to 0.52 mg/L as Si; and
c. 5.9 mg/L as SiO_2: average increase was 0.32 mg/L with a range 0.16 to 0.49 mg/L Si.

The average dose concentration of each setting immediately after dosing was;

Figure E.2.8.1.1
Daily Changes in pH of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

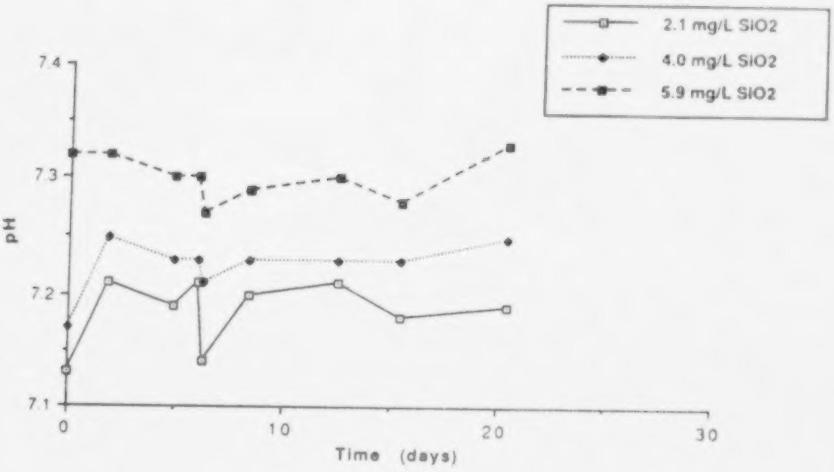


Figure E.2.8.2.1
Daily Changes in pH of the Experimental Water for
the Immersion of Ductile Iron at the Silicate Concentration 6.9 mg/L as SiO_2

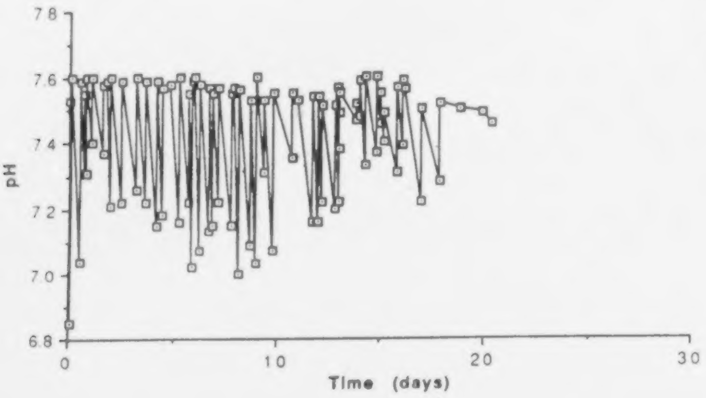


Figure E.2.8.2.2
Daily Changes in pH of the Experimental Water for
the Immersion of Ductile Iron at the Silicate Concentration 10.0 mg/L as SiO_2

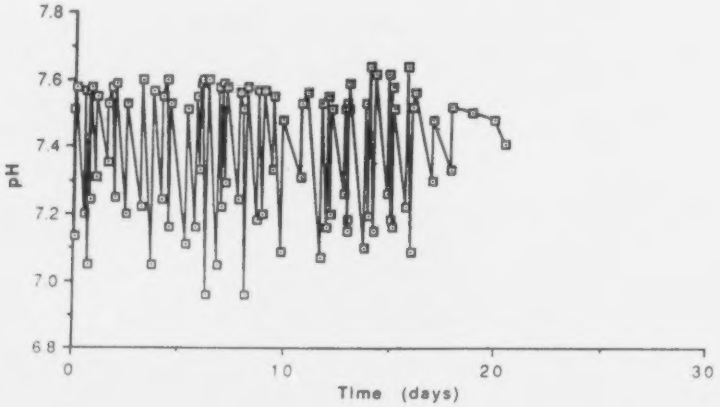


Figure E.2.8.2.3
Daily Changes in pH of the Experimental Water for
the Immersion of Ductile Iron at the Silicate Concentration 13.4 mg/L as SiO_2

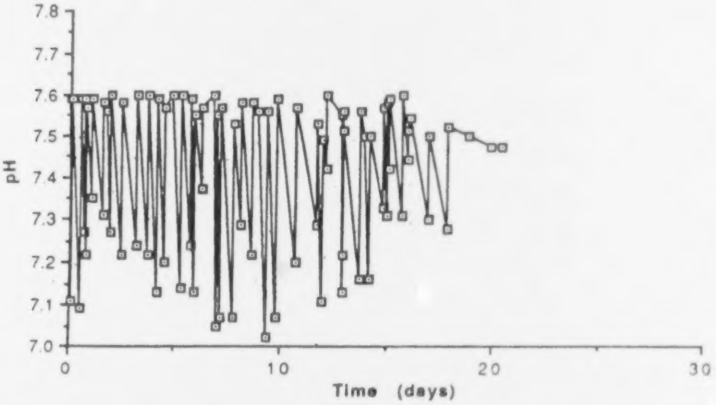
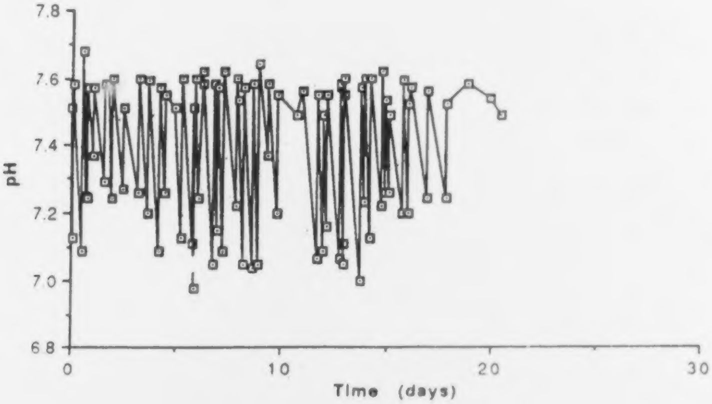


Figure E.2.8.2.4
Daily Changes in pH of the Experimental Water for
the Immersion of Ductile Iron at the Silicate Concentration 21.0 mg/L as SiO_2



a. 2.1 mg/L as SiO_2: average was 1.09 mg/L as Si;

b. 4.0 mg/L as SiO_2: average was 2.14 mg/L as Si; and

c. 5.9 mg/L as SiO_2: average was 3.08 mg/L as Si.

In order for silicate to deposit on a metal surface, there must be an existing layer of corrosion scale. Copper, unlike ductile iron, tarnishes and does not produce the scale necessary to deposit silicate. Consequently, protection against corrosion using sodium silicate, occurs only from changes in alkalinity and pH from chemical addition.

E.2.9.2 Ductile Iron Experiments

Figure E.2.9.2.1 shows the decreases in silicate concentration of the experimental waters, for the immersion of ductile iron at different silicate concentrations. The average decrease and range by which the silicate concentration changed for each setting during an average 3 day liquid retention time was:

a. 6.9 mg/L as SiO_2: average change was -0.79 mg/L with a range of -1.46 to -0.37 mg/L as Si;

b. 10.0 mg/L as SiO_2: average change was -1.54 mg/L with a range of -2.35 to -1.10 mg/L as Si;

c. 13.4 mg/L as SiO_2: average change was -2.11 mg/L with a range of -2.88 to -1.29 mg/L as Si; and

d. 21.0 mg/L as SiO_2: average change was -3.76 mg/L with a range of -4.63 to -2.60 mg/L as Si.

Figure E.2.9.1.1
Weekly Changes in Silicate Concnetration of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

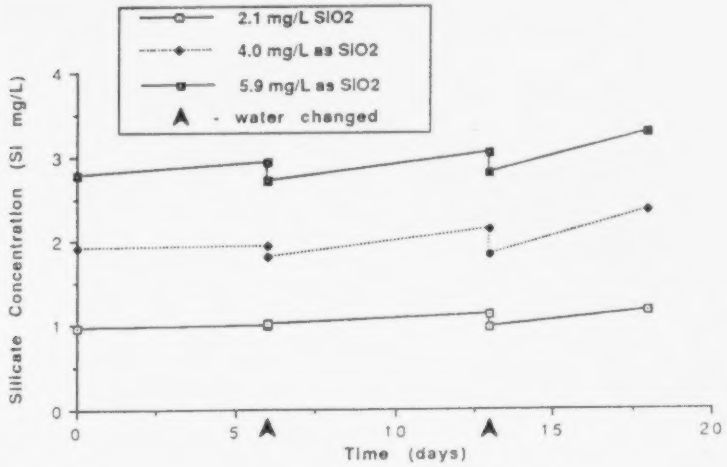
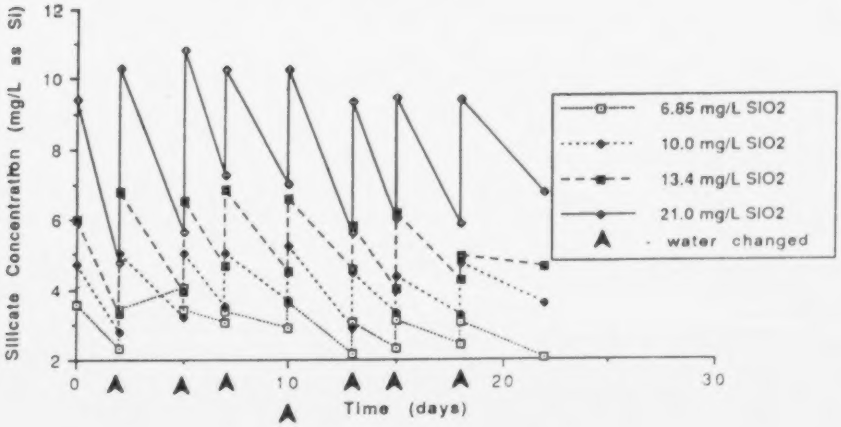


Figure E.2.9.2.1
Changes in Silicate Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations



E.2.10 Sodium Concentration

E.2.10.1 Copper Experiments

Figure E.2.10.1.1 shows the weekly changes in sodium concentration of the experimental waters, for the immersion of copper at different silicate concentrations. The average increase and range by which the sodium concentration changed for each setting during a weekly retention time was:

a. 2.1 mg/L SiO_2 concentration: average increase was 6.07 mg/L with a range of 5.08 to 6.58 mg/L as Na^+;
b. 4.0 mg/L SiO_2 concentration: average increase was 4.73 mg/L with a range of 4.26 to 5.11 mg/L as Na^+; and
c. 5.9 mg/L SiO_2 concentration: average increase was 5.40 mg/L with a range of 4.46 to 6.99 mg/L as Na^+.

Shown are the changes in sodium concentration as increasing with increasing silicate dosage.

E.2.10.2 Ductile Iron Experiments

Figure E.2.10.2.1 shows the changes in sodium concentration of the experimental waters, for the immersion of ductile iron at different silicate concentrations. The average increase and range by which the sodium concentration changed for each setting during a 3 day liquid retention time was:

a. 6.9 mg/L as SiO_2: average increase was 25.99 mg/L with a range of 20.26 to 35.16 mg/L as Na^+;

Figure E.2.10.1.1
Weekly Changes in Sodium Concnetration of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

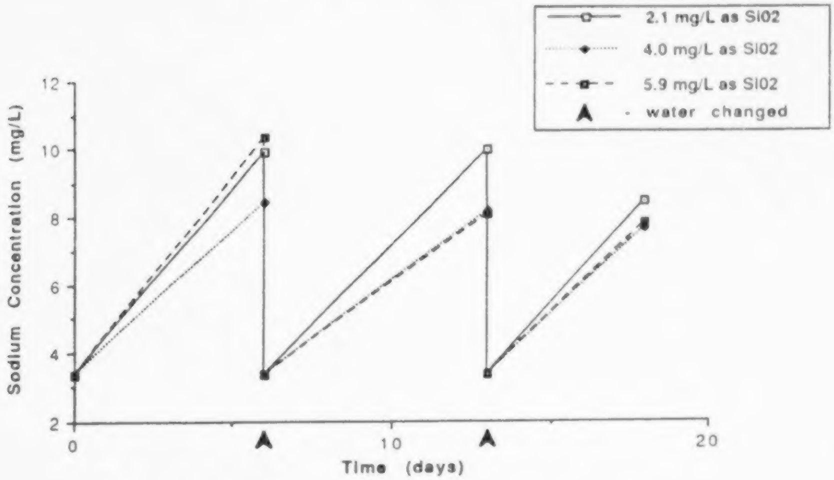
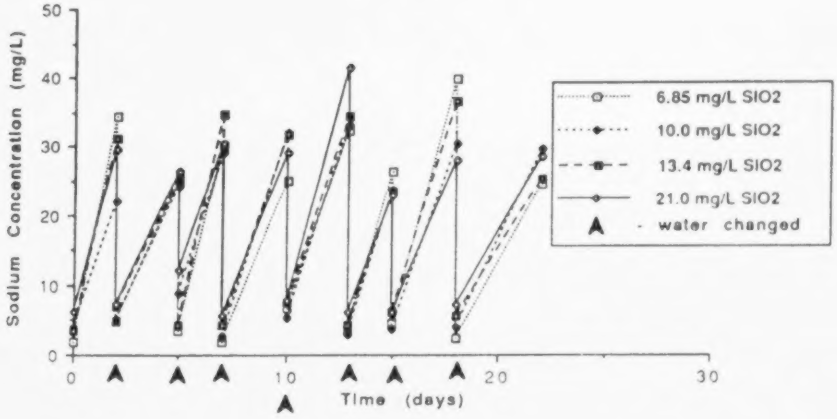


Figure E.2.10.2.1
Changes in Sodium Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations



b. 10.0 mg/L as SiO_2: average increase was 23.44 mg/L with a range of 18.12 to 29.47 mg/L as Na^+;
c. 13.4 mg/L as SiO_2: average increase was 25.03 mg/L with a range of 18.34 to 30.59 mg/L as Na^+; and
d. 21.0 mg/L as SiO_2: average increase was 22.15 with a range of 16.63 to 33.69 mg/L as Na^+.

The increases in sodium concentration of each setting is attributed to the contribution of sodium hydroxide and sodium silicate additions and from liquid losses due to evaporation.

E.2.11 Sulfate Concentration

E.2.11.1 Copper Experiments

Figure E.2.11.1.1 shows the weekly increases in sulfate concentration of the experimental waters, for the immersion of copper at different silicate concentrations. The average increase and range by which the sulfate concentration changed for each setting during a weekly retention time was:

a. 2.1 mg/L SiO_2 concentration: average increase was 0.9 mg/L with a range of 0.6 to 1.2 mg/L as SO_4^{2-};
b. 4.0 mg/L SiO_2 concentration: average increase was 0.9 mg/L with a range of 0.4 to 1.4 mg/L as SO_4^{2-}; and
c. 5.9 mg/L SiO_2 concentration: average increase was 1.0 mg/L with a range of 1.0 to 1.1 mg/L as SO_4^{2-}.

The weekly increases are from liquid losses due to evaporation.

E.2.11.2 Ductile Iron Experiments

Figure E.2.11.2.1 shows the changes in sulfate concentration of the experimental waters, for the immersion of ductile iron at different silicate concentrations. The average decrease and range by which the sulfate concentration changed for each setting during an average 3 day liquid retention time was:

a. 6.9 mg/L SiO_2 concentration: average change was -1.32 mg/L with a range of -1.83 to -0.35 mg/L as SO_4^{2-};

b. 10.0 mg/L SiO_2 concentration: average change was -1.42 mg/L with a range of -2.58 to -0.60 mg/L as SO_4^{2-};

c. 13.4 mg/L SiO_2 concentration: average change was -1.22 mg/L with a range of -2.58 to -0.11 mg/L as SO_4^{2-}; and

d. 21.0 mg/L SiO_2 concentration: average change was -1.00 mg/L with a range of -2.58 to -0.11 mg/L as SO_4^{2-}.

E.2.12 Temperature

The temperature at which the experiments were performed, ranged from 5 to 7 °C.

E.2.13 Total Hardness Concentration

E.2.13.1 Copper Experiments

Figure E.2.13.1.1 shows the weekly changes in the total hardness concentration of the experimental waters, for the immersion of copper at different silicate concentrations. The average increase and range by which the

Figure E.2.11.1.1
Weekly Changes in Sulfate Concnetration of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

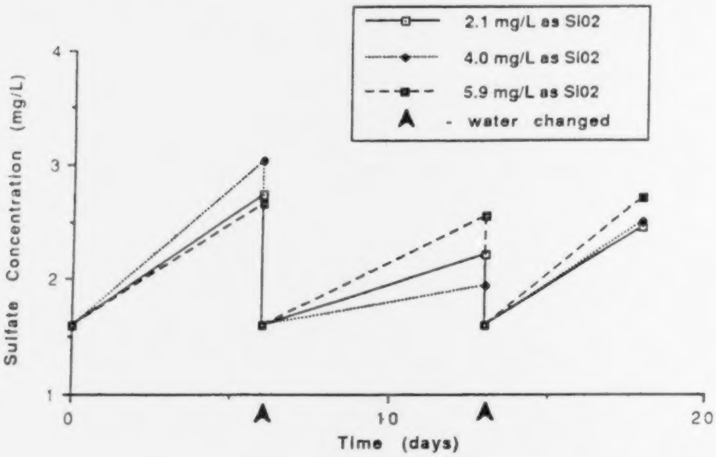
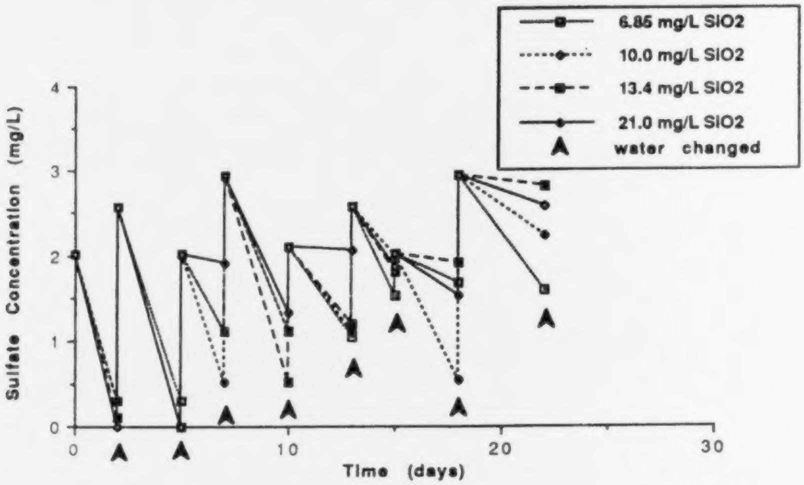


Figure E.2.11.2.1
Changes in Sulfate Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations



total hardness concentration changed for each setting for a weekly retention time was:

a. 4 mg/L SiO_2 concentration: average increase was 2.1 mg/L with a range of 1.6 to 2.8 mg/L as $CaCO_3$;
b. 8 mg/L SiO_2 concentration: average increase was 1.4 mg/L with a range of 0.8 to 2.2 mg/L as $CaCO_3$; and
c. 12 mg/L SiO_2 concentration: average increase was 1.0 mg/L with a range of 0.4 to 2.0 mg/L as $CaCO_3$.

The hardness concentration of each setting increased slightly from liquid losses due to evaporation. The magnitude of the increases were similar.

E.2.13.2 Ductile Iron Experiments

Figure E.2.13.2.1 shows the changes in the total hardness concentration of the experimental waters, for the immersion of ductile iron at different silicate concentrations. The average change and range by which the total hardness concentration changed for each setting for an average liquid retention time of 3 days was:

a. 6.9 mg/L as SiO_2: average change was -0.7 mg/L with a range of -2.0 to 0.5 mg/L as $CaCO_3$;
b. 10.0 mg/L as SiO_2: average increase was 0.2 mg/L with a range of -1.0 to 2.0 mg/L as $CaCO_3$;
c. 13.4 mg/L as SiO_2: average change was -0.2 mg/L with a range of -1.0 to 1.2 mg/L as $CaCO_3$; and
d. 21.0 mg/L as SiO_2: average increase was 0.8 mg/L with a range of -2.8 to 1.4 mg/L as $CaCO_3$.

Figure E.2.13.1.1
Weekly Changes in Total Hardness Concnetration of the Experimental Waters for the Immersion of Copper at Different Silicate Concentrations

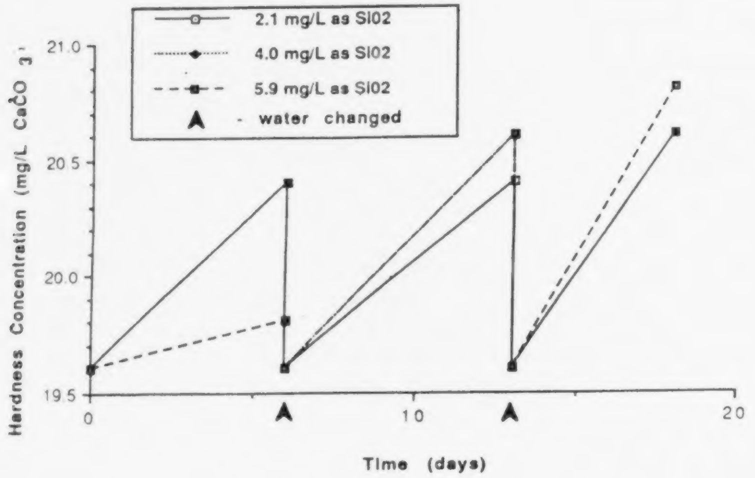
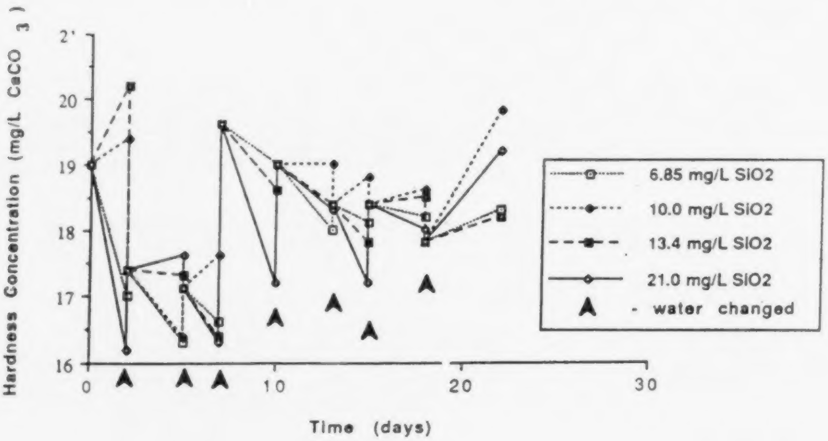


Figure E.2.13.2.1
Changes in Total Hardness Concentration of the Experimental Waters for the Immersion of Ductile Iron at Different Silicate Concentrations



E.2.14 Turbidity

E.2.14.1 Copper Experiments

Figure E.2.14.1.1 shows the weekly changes in turbidity of the experimental waters, for the immersion of copper at different silicate concentrations. The average increase and range by which the turbidity changed for each setting during a weekly liquid retention time was:

a. 2.1 mg/L SiO_2 concentration: average increase was 0.5 with a range of 0.4 to 0.6 NTU;
b. 4.0 mg/L SiO_2 concentration: average increase was 1.0 with a range of 0.7 to 1.3 NTU; and
c. 5.9 mg/L SiO_2 concentration: average increase was 0.6 with a range of 0.5 to 1.0 NTU.

E.2.14.2 Ductile Iron Experiments

Figure E.2.14.2.1 shows the changes in turbidity of the experimental waters, for the immersion of ductile iron at different silicate concentrations. The average increase and range by which the turbidity changed for each setting during an average 3 day liquid retention time was:

a. 6.9 mg/L as SiO_2: average increase was 11.0 with a range of 0.2 to 25.6 NTU;
b. 10.0 mg/L as SiO_2: average increase was 12.3 with a range of 1.8 to 27.6 NTU;
c. 13.4 mg/L as SiO_2: average increase was 10.1 with a range of 0.8 to 28.6 NTU; and

Figure E.2.14.2.1
Changes in Turbidity of the Experimental Waters for
the Immersion of Ductile Iron at Different Silicate Concentrations

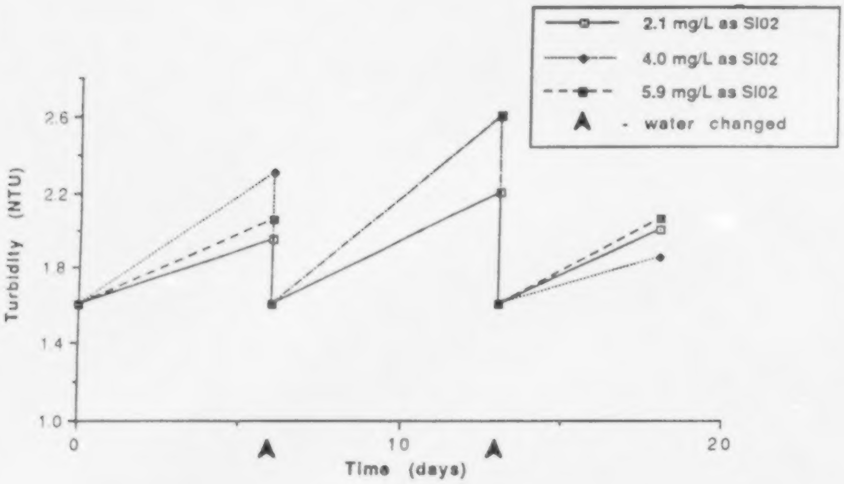
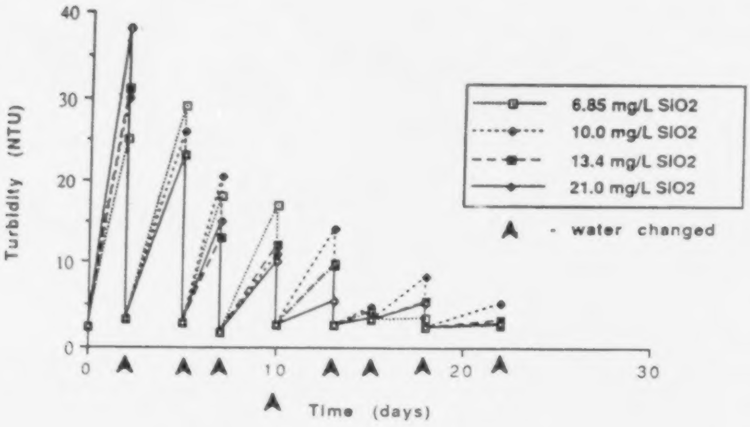


Figure E.2.14.1.1
Weekly Changes in Turbidity of the Experimental Waters for the Immersion
of Copper at Different Silicate Concentrations



d. 21.0 mg/L as SiO_2: average increase was 10.3 with a range of 0.4 to 35.6 NTU.

The increases in turbidity are shown decreasing with time, from the removal of coupons and from a reduction in corrosion.

Appendix F

Coupon Handling and Shipping Instructions

Appendix F

Coupon Handling and Shipping Instructions

INSTALLMENT OF COUPONS

***Please avoid touching the metal coupons during installation and removal. Handle the metal coupons by either their hanging hooks, or by using the thongs provided.**

1) The coupons, to be installed will be delivered already assembled, that is, the coupons will be attached to their hanging hooks, and will only require placement. The hanging hooks are of two lengths (ie. 50 mm and 100 mm). The hanging rods are labelled to indicate which hook length each hanging rod is for. Be sure to hang only those coupons with 50 mm length hooks on the hanging rods labelled, hook length 50 mm, and visa versa for the 100 mm length hooks.

2) Install the coupons in the positions left vacant by the coupons early removed. Ensure the coupon hook length corresponds to the correct hanging rod and position the hanging hook firmly on the hanging rod where it has been notched.

3) To install, remove coupon assembly from its zip lock bag. Gently unwrap the coupon assembly from its plastic. Please do not touch the coupon.

4) Using thongs or lifting the metal coupon by its hanging hook, install the coupon into the coupon holding apparatus. Ensure the coupons are hung on the correct hanging rods, according to the coupon's hook length.

5) Repeat the same procedure for the remaining coupons to be installed for each apparatus.

6) Ensure to record all necessary information on the sheet labelled; **information required.**

INFORMATION REQUIRED

***This information sheet is to be used to record the dates the coupon sets were removed and/or installed for each apparatus. Record any problems associated to the operation of each apparatus (ie. leaks, excessive accumulation of sediment in apparatus, etc.)**

Pumphouse 2

APPARATUS A:
Date coupons removed and/or installed: ______________________________

Flow Rate: ______________________________

APPARATUS B:
Date coupons removed and/or installed: ______________________________

Flow Rate: ______________________________

REMARKS: ______________________________

Pumphouse 2

APPARATUS A:
Date coupons removed and/or installed: ______________________________

Flow Rate: ______________________________

APPARATUS B:
Date coupons removed and/or installed: ______________________________

Flow Rate: ______________________________

REMARKS: ______________________________

Appendix G

Preliminary Investigation into the Handling of Coupons From Yellowknife, N.W.T.

Appendix G
Preliminary Investigation into the Handling of Coupons from Yellowknife

Results of the investigation to determine
the effect of packaging for an exposure time of five and half days.

Coupon Set	Corrosion Rate	Average Corrosion Rate $g/(m^2d)$
1) Metal coupons removed immediately and annalyzed.	5.21 5.68	5.45
2) Metal coupons removed, dried properly, packaged, and analyzed after 5.5 days.	5.43 5.67	5.55
3) Metal coupons removed, not properly dried, packaged, and analyzed after 5.5 days.	11.15 10.82	10.98

Appendix H

Ten-Point Scale of the Corrosion Resistance of Metals

Appendix H

Ten-Point Scale of the Corrosion Resistance of Metals
(GOST 5272-50)

Resistance Properties	Rate of Corrosion (mm/year)	Point
Completely resistant metals	0.001	0
Highly resistant metals	0.001-0.005	1
	0.005-0.01	2
Resistant metals	0.01-0.05	3
	0.05-0.1	4
Fairly resistant metals	0.1-0.5	5
	0.5-1.0	6
Metals exhibiting low resistance	1-5	7
	5-10	8
Non-resistant metals	above 10	9

Reference; Bakhvalov, G.T., Turkovskaya, A.V., 1965. Corrosion And Protection of Metals. Pergamon Press, Oxford, p 98.

Limitations to using scale; This scale is not valid for intercystalline corrosion. As well, the scale does not take into consideration service requirements. That is, what degree of corrosion can the material undergoe before being rendered unfit for service.

Appendix I

Example Calculation of the langelier Saturation Index for Water Quality Changes Associated from the Addition of Lime and Carbon Dioxide

Appendix I

Example Calculation of the Langelier Saturation Index For Water Quality Changes Associated From the Addition of Lime and Carbon Dioxide.

Reference: EPA, 1984. Corrosion Manual for Internal Corrosion of Water Distribution Systems., U.S. Environmental Protection Agency, Washington, D.C., EPA 570/9-84-001, pp 43-47.

a. Water quality for Yellowknife River water (no chemicals added);

Average Total Hardness: 20 mg/L as $CaCO_3$
Calcium Hardness: 14 mg/L as $CaCO_3$
Total Alkalinity: 18 mg/L as $CaCO_3$
pH: 7.2
TDS: 30 to 40 mg/L
Temperature: 5 °C

To calculate the Langelier Saturation Index (LSI) the following equations are used;

$$pHs = A + B - \log[Ca^{++}] - \log \text{total alkalinity}$$

$$LSI = pH\ (\text{actual}) - pHs$$

Calculation of the LSI value for the Yellowknife River Water is as follows;

For a water temperature of 5 °C the value for constant A from Table 6.2 (EPA, 1984) is 2.48. For a TDS of 40 mg/L the value for constant B is 9.74 from Table 6.3 (EPA, 1984).

$$\log[Ca^{++}] = \log[14] = 1.15$$

log total alkalinity = log 18 = 1.26

pHs = 2.48 + 9.74 - 1.15 - 1.26 = 9.81

LSI = 7.2 - 9.81 = - 2.61 LSI< 0, very aggressive, will definitely dissolve CaCO3

Treatment with Lime and Carbon Dioxide

To produce a water with a total hardness of 75 mg/L as $CaCO_3$ and pH of 8.5, a total of 55 mg/L as $CaCO_3$ of lime is required. This will require adding approximately 41 mg/L of lime as $Ca(OH)_2$. The amount of carbon dioxide needed to adjust the pH to 8.5 is 110 mg/L as $CaCO_3$. The resultant water quality is then;

Note: The addition of carbon dioxide to water does not cause a net increase alkalinity. Instead it increases the total carbonic concentration and acidity.

Total Hardness: 75 mg/L as CaCO3
Calcium Hardness: 69 mg/L as CaCO3
Total Alkalinity: 73 mg/L as CaCO3
pH: 8.5
TDS approximately 100 mg/L
Temperature: 5 °C

Calculation of the LSI is;

Constants; A = 2.48
B = 9.77

log[Ca++] = log[69] = 1.84

log total alkalinity = log 73 = 1.86

pHs = 2.48 + 9.77 - 1.84 - 1.86 = 8.55

LSI = 8.5 - 8.55 = -0.05 LSI<0, will dissolve $CaCO_3$

if the pH of the treated water is

reduced to pH 7.5 the LSI value decreases to -1.05
which will definitely dissolve $CaCO_3$.

The addition of lime and carbon dioxide to achieve a treated water of pH 8.5 and a total hardness of 75 mg/L as $CaCO_3$ will only just saturate the water with respect to $CaCO_3$. The addition of more lime is required to supersaturate the water. However, this means adding large amounts of lime which is uneconomical.

Limitations; The LSI is useful only to estimate a water's tendency to precipitate $CaCO_3$. It does not provide information as to the amount that might be precipitated, nor is it a measurement of corrosivity (EPA, 1984). Waters with a negative LSI value have in some cases been reported to deposit $CaCO_3$ (AWWA, 1985). The LSI is a valuable monitoring tool only when used in conjunction with other indirect or direct corrosion monitoring methods.

Appendix J

Media Ingredients

Media Ingredients

1. B_{10} Broth

K_2HPO_4	0.8 g	$CaSO_4$ (sat. sol'n)	10 mL
KH_2PO_4	0.2 g	Yeast Extract	5 g
$MgSO_4$	0.2 g	Peptone	5 g
NaCl	0.2 g	Ferric Phosphate	4.7 g
$MnSO_4$	trace	Deionized Water	1000 mL
Na_2MoO_4	trace		

2. Butlins Medium

K_2HPO_4	0.5 g
NH_4Cl	1.0 g
Na_2SO_4	2.0 g
$CaCl_2{*}\ 6H_2O$	0.1 g
$MgSO_4{*}\ 7H_2O$	1.0 g
Sodium Lactate	2.5 mL of a 60% (v/v) solution
Yeast Extract	1.0 g
$FeSO_4$	0.002 g
Deionized Water	1000 mL

Adjust to pH 7.5. Autoclave at 121 °C, 20 minutes

3. Winogradsky Medium for Iron Bacteria

NH_4NO_3	0.5 g
$NaNO_3$	0.5 g
K_2HPO_4	0.5 g
$MgSO_4{*}\ 7H_2O$	0.5 g
$CaCl_2{*}\ 6H_2O$	0.2 g
Ferric Ammonium Citrate	10 g
Deionized Water	1000 mL

4. Starkey Medium for Sulfur-oxidizing Bacteria

$(NH_4)_2SO_4$	0.2 g
KH_2PO_4	3 g
$MgSO_4 * 7H_2O$	0.5 g
$CaCl_2 * 6H_2O$	0.25 g
$Fe_2(SO_4)_3 * 9H_2O$	0.01 g
Sulfur Powder	10 g

pH 7.5

Appendix K

Statistical Methods Used

Small Sample Statistical Test for the Difference between Two Means

The following are the statistical equations used in the statisitical analysis of the corrosion rate data:

A. Mean: $X = \sum(X_i)/(n)$

n = no# of samples in test

Xi = data values

B. Standard Deviation: $S^2 = \sum(X - X_i)^2/(n - 1)$

C. Small sample statisitical t-test for the difference between two means:

Ho: $U_1 = U_2$

$Do = U_1 - U_2$

X_1 = sample mean of population 1

X_2 = sample mean of population 2

n_1 = no# of samples for population 1

n_2 = no# of samples for population 2

t-Test : $t = ((X_1 - X_2) - Do)/(S(1/n_1 + 1/n_2)^{-2})$

(two tail test)

Degrees of freedom = $n_1 + n_2 - 2$

Pooled Estimator of S^2

$S^2 = ((n_1 - 1)S_1{}^2 + (n_2 - 1)S_2{}^2)/(n_1 + n_2 - 2)$

D. Confidence Level:

The following equation is used to calculate the confidence level:

$(X_1 - X_2) +/- t_{\alpha/2} S(1/n_1 + 1/n_2)^{-2}$

$t_{\alpha/2}$ = t value corresponding to the degrees of freedom and 95% confidence level

Appendix L

Comparison of Yellowknife's Corrosion Problem to That of Greater Vancouver, B.C

Appendix L

Comparison of Yellowknife's Corrosion Problem to That for Greater Vancouver, B.C. and Edmonton, Alberta.

To assess the severity of the corrosion problem the City of Yellowknife is presently experiencing, the study's results are compared to a similar study conducted for the Greater Vancouver area. Refer to Figure L.1 for comparison of Yellowknife's corrosion problem to the Greater Vancouver area. The experimental methodologies are campared in order to account for the many factors, both physical and chemical which can influence corrosion..

Shown in Table L.1 is the water quality characteristics as very similar for both the Yellowknife and Vancouver study. The only differences are the physical characteristics. The Vancouver study was performed at approximately 20 ^{0}C or four times that of Yellowknife's water temperature. Temperature can influence the corrosion phenomena by affecting reaction rates, gas solubility and the rate of scale formation (AWWA, 1985). Increasing temperature will increase reaction rates which will assist in a faster scale formation offering early protection by passivation from corrosion products. Flow velocities were considered not significantly different between studies to have greatly influence corrosion. Table L.1 summarizes the differences in both water quality and physical characteristics associated to each study.

Figure L.1 shows the City of Yellowknife as experiencing greater problems in corrosion of its ductile iron piping than for the Greater Vancouver area. Table L.2 summarizes the long term average corrosion rates;

The average corrosion rate for ductile iron for Yellowknife's raw water was 25% higher than the average rate observed for the Greater Vancouver area.

Figure L.2 shows the City of Yellowknife as experiencing lower rates of corrosion for copper exposed to its raw water compared to the raw water used in the Greater Vancouver area. Treatment of Yellowknife's supply water with chlorine, fluoride and during the winter, heat, increases the water's corrosivity above that reported for the Greater Vancouver area. Table L.3 summarizes the long term average corrosion rates for both Yellowknife's raw and treated water compared to the Greater Vancouver area. The average corrosion rate for Vancouver's raw water was 31% higher than Yellowknife's raw water corrosion rate. In addition, Yellowknife's treated water corrosion rate was 48% higher than the rate observed for the Greater Vancouver area.

In conclusion, for ductile iron, Yellowknife's raw water is more corrosive than the raw water for the Greater Vancouver area. For copper the raw water for the Greater Vancouver area is more corrosive.

Table L.1
Comparison of Water Quality and Physical Characteristcs for Yellowknife's and Greater Vancouver 's Raw Water

Parameter (mg/L)	Vancouver Raw Water (range)	Yellowknife Raw Water (range)
Temperature, ^{0}C	20.1	5
pH	7.05-7.25	6.8-7.5
Dissolved Oxygen	9.81-8.25	Saturated
Chloride	1.16-0.98	1.1-2.5
Sulfate	1.94-2.92	1.8-3.9
Calcium	4.04-4.72	4.37-5.46
Total Alkalinity as $CaCO_3$	15.9-20.7	16.6-20.2
Total Hardness as $CaCO_3$	11.6-16.5	18.4-19.8
Chlorinated	No	No
Metal Type	Ductile Iron	Ductile Iron
Velocity, m/s	0.0002	0.0005

Figure L.1
Corrosion Rates of Ductile Iron for Yellowknife's Raw and Treated Water Compared to Those for the Greater Vancouver Area

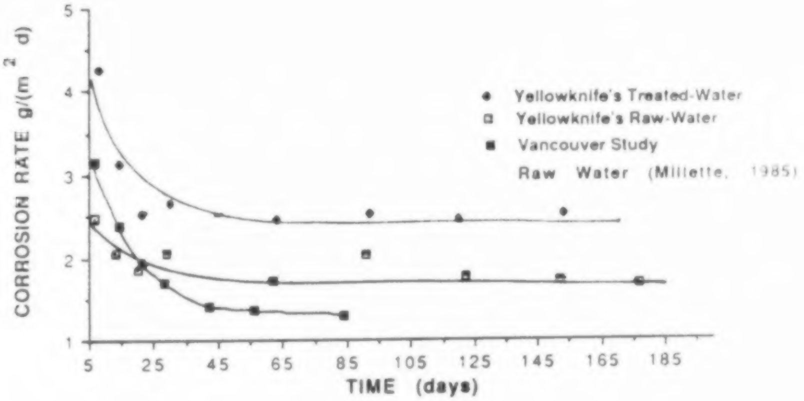


Table L.2
Comparison of the Long Term Average Corrosion Rates of Ductile Iron Between Yellowknife's Raw and Treated Waters to the Greater Vancouver Raw Water

Average Corrosion Rates g/(m^2 d)		
Vancouver	Yellowknife's	
Raw Water	Raw Water	Treated Water
1.40	1.88	2.63

Figure L.2
Corrosion Rates of Copper for Yellowknife's Raw and Treated Water Compared to Those for the Greater Vancouver Area

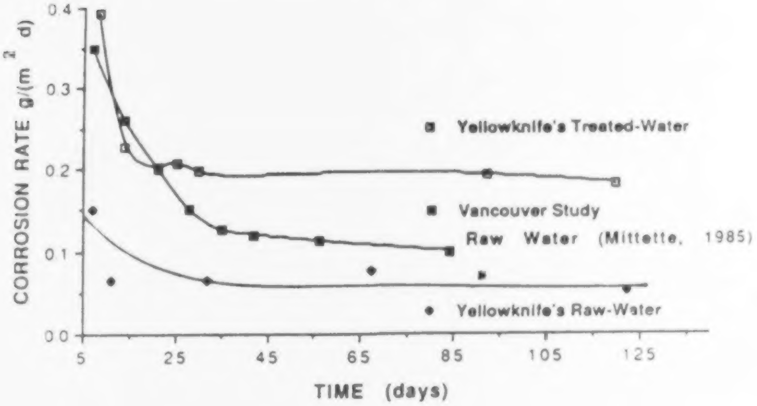


Table L.3
Comparison of the Long Term Average Corrosion Rates of Copper Between Yellowknife's Raw and Treated Water to the Greater Vancouver Raw Water

Average Corrosion Rate g/(m^2 d)		
Vancouver	Yellowknife's	
Raw Water	Raw Water	Treated Water
0.1	0.069	0.194